

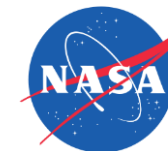
Planetesimal Formation by the Streaming Instability



Wladimir Lyra
New Mexico State University

Las Cruces NM, USA

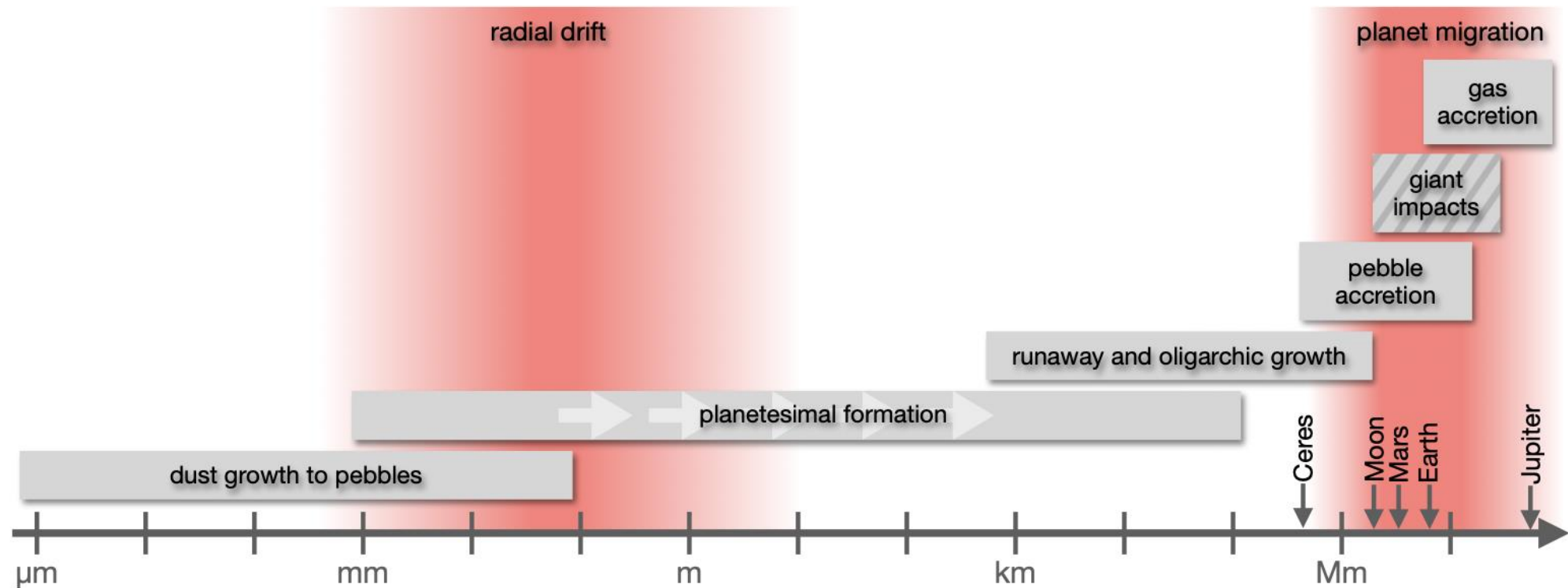
PFITS+ (Planet Formation in the Southwest)



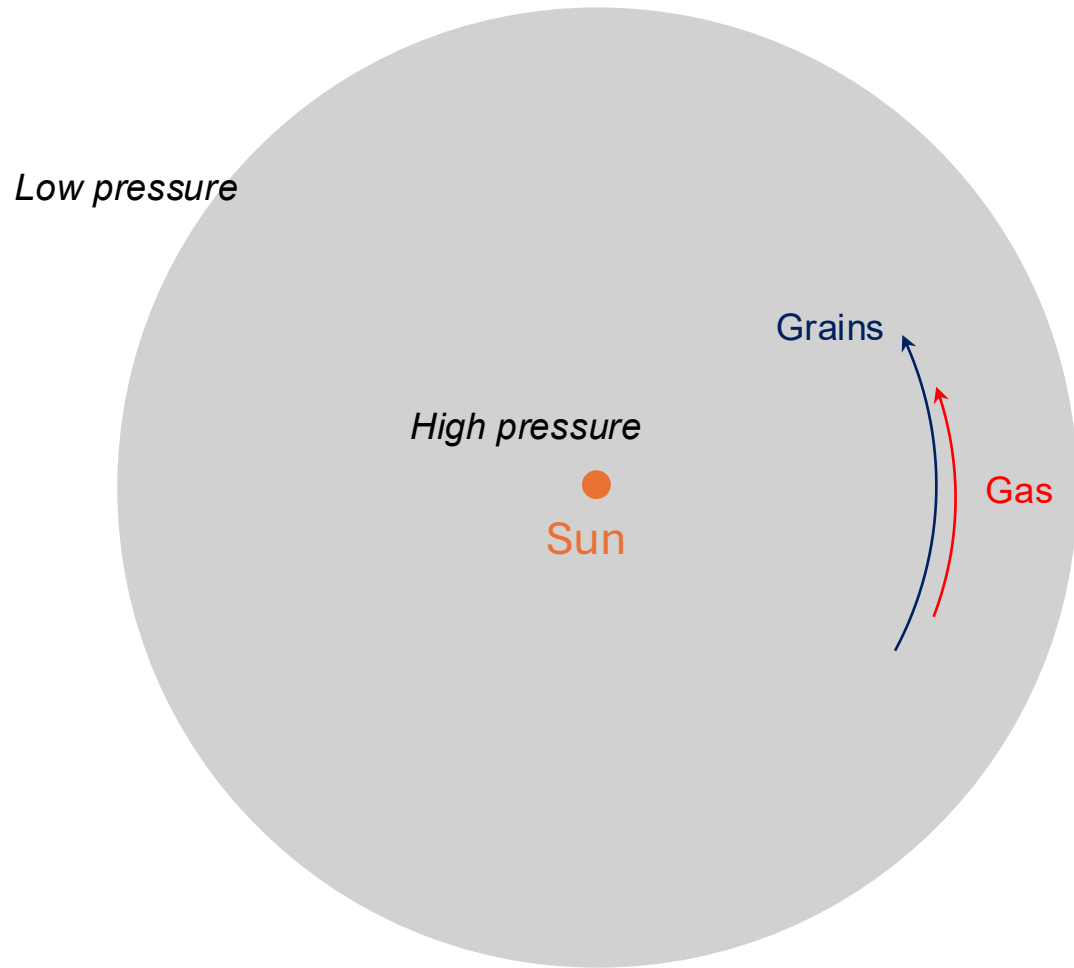
StarPlan Retreat

Ystad, Sweden - Apr 13-17, 2026

Planet Formation Ladder



Headwind and Dust Drift

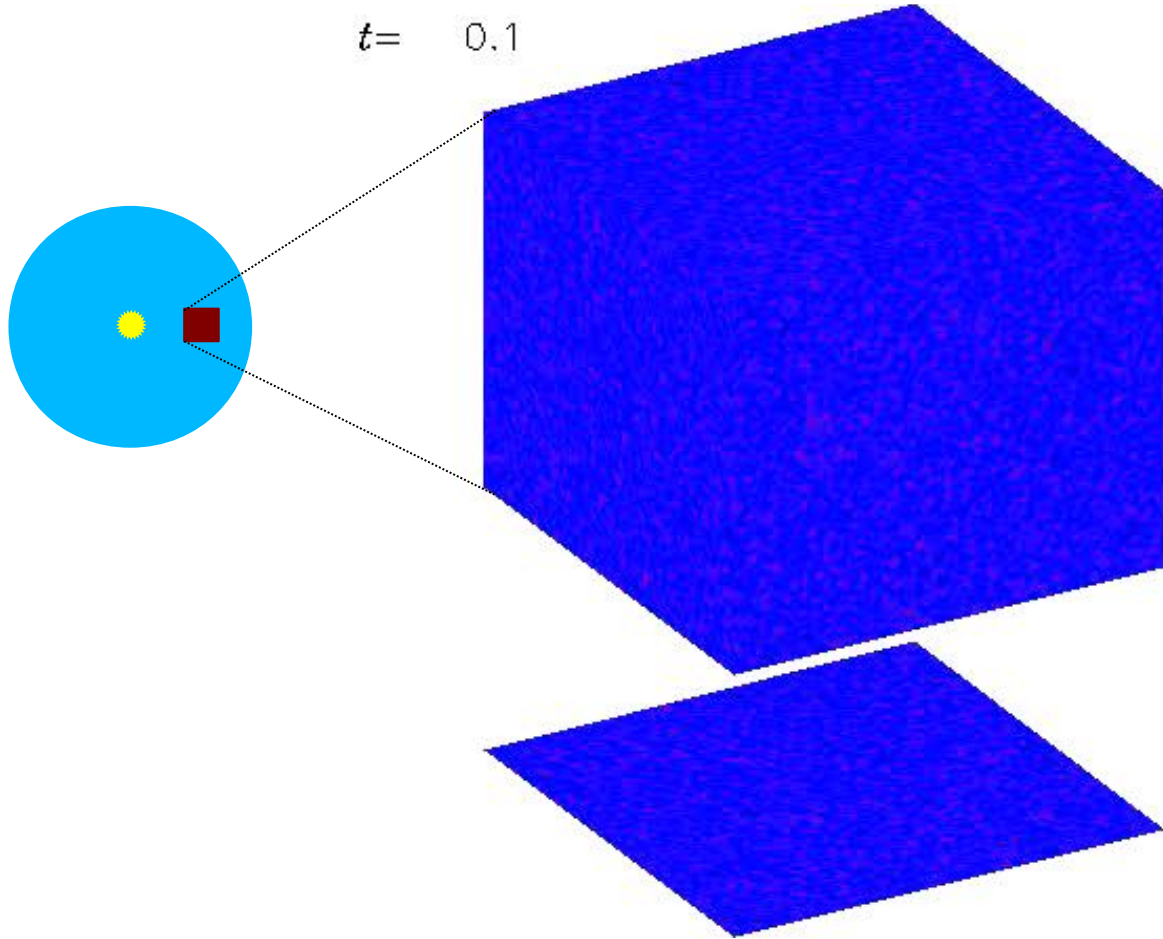


The **gas** has some pressure support (sub-Keplerian).

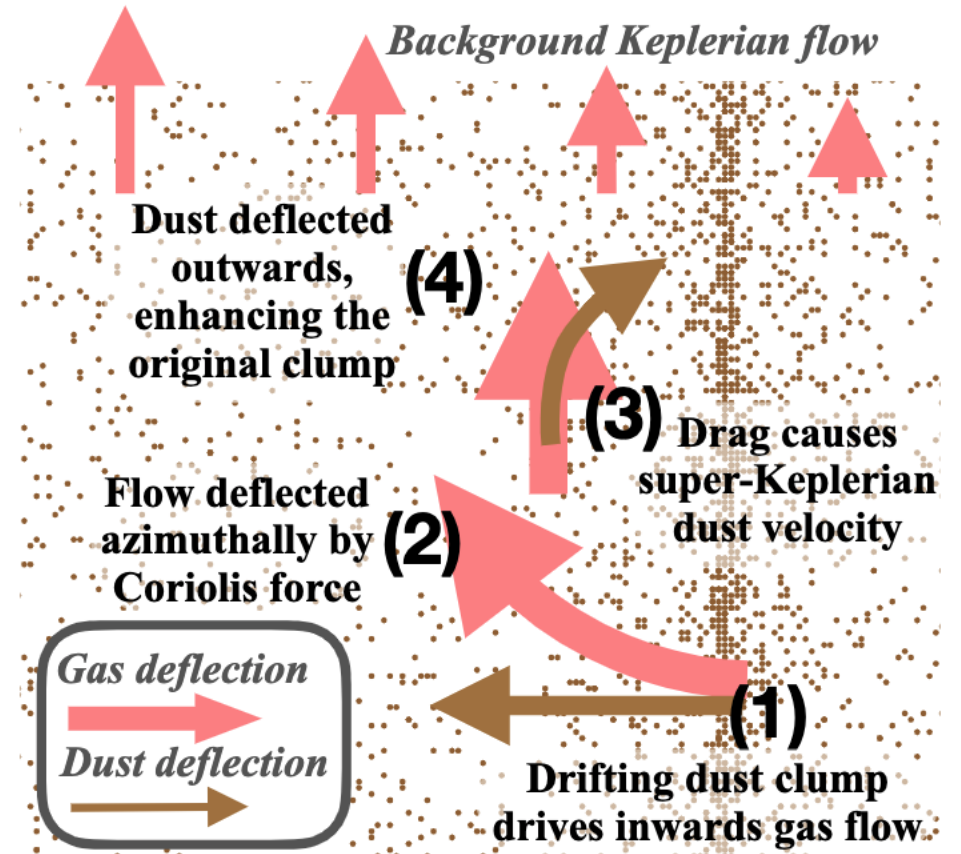
The **grains** do not feel gas pressure (Keplerian).

Streaming Instability

The grain drift is hydrodynamically unstable



Johansen & Youdin (2007)



Lesur et al. (2023)

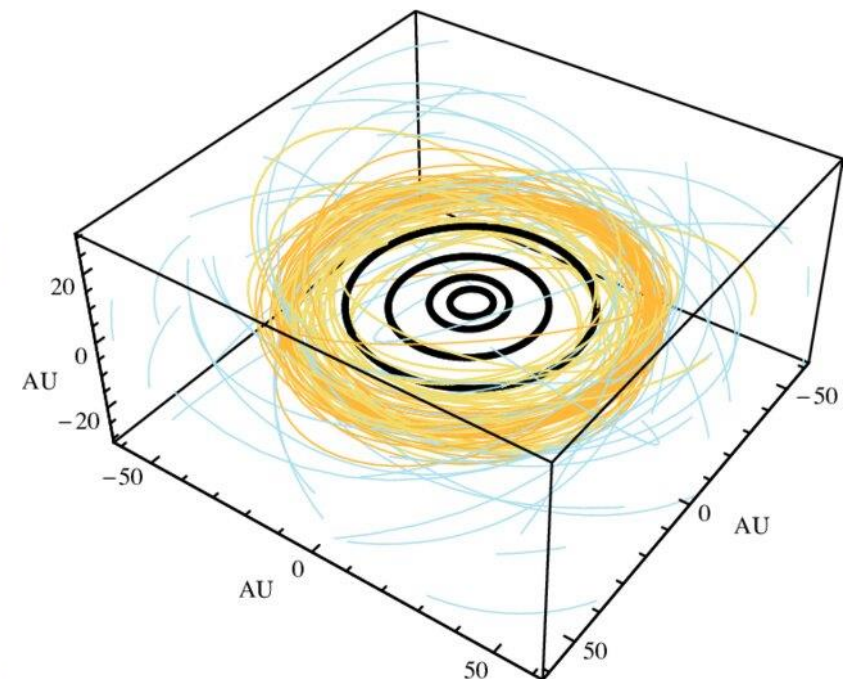
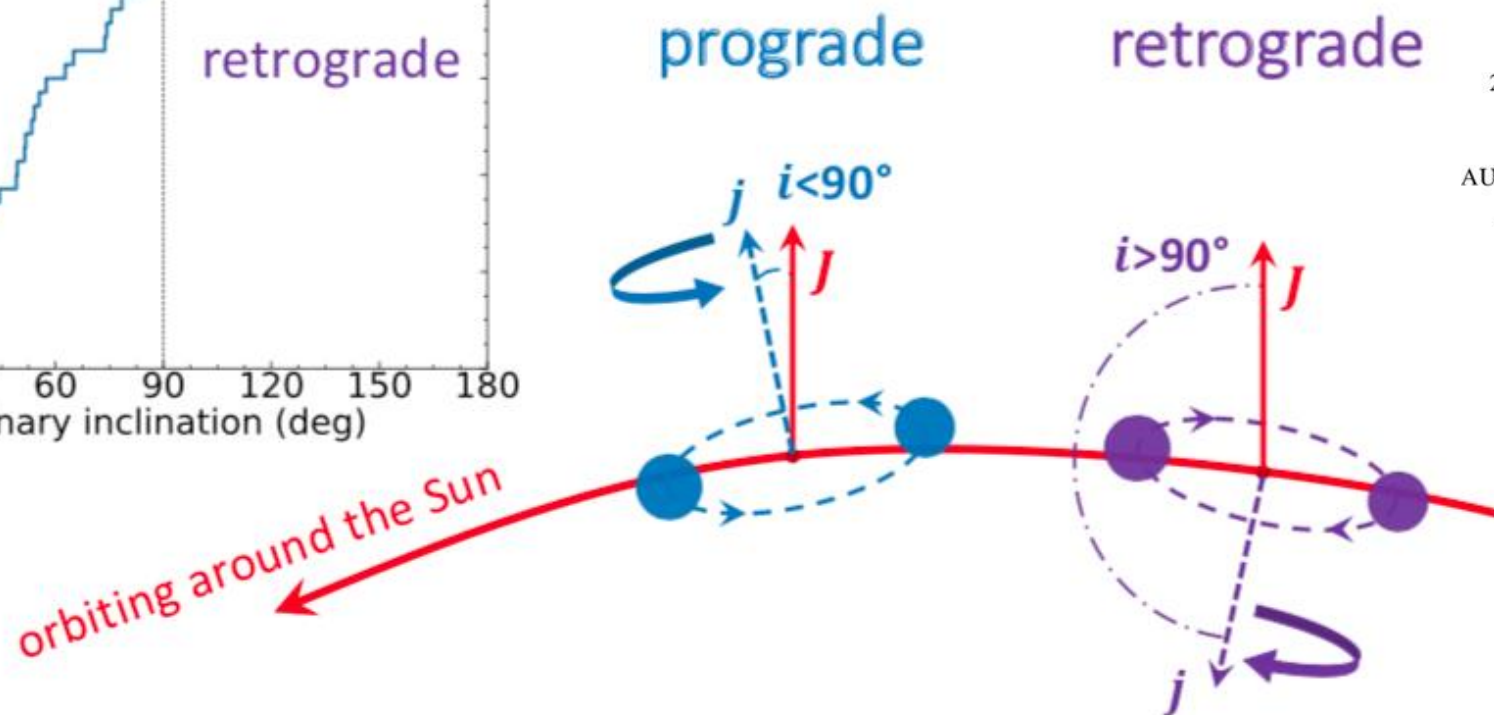
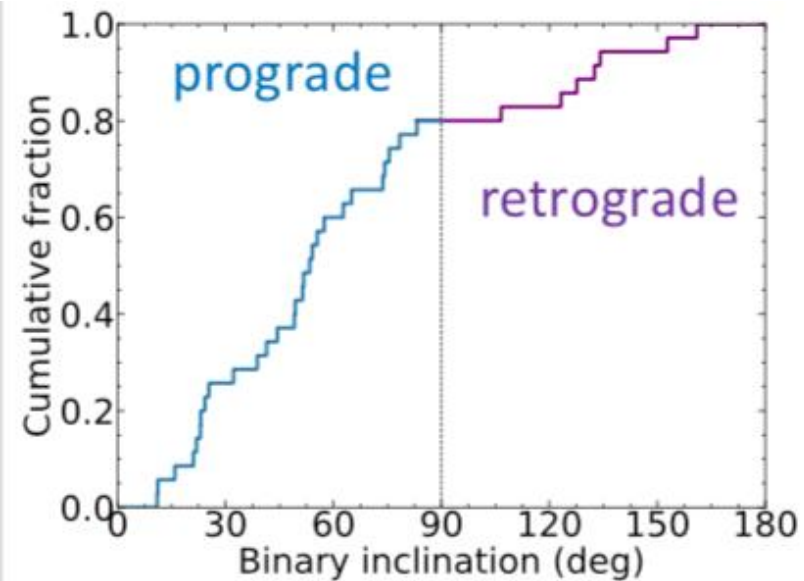


nature astronomy

Fingerprints of
streaming instability

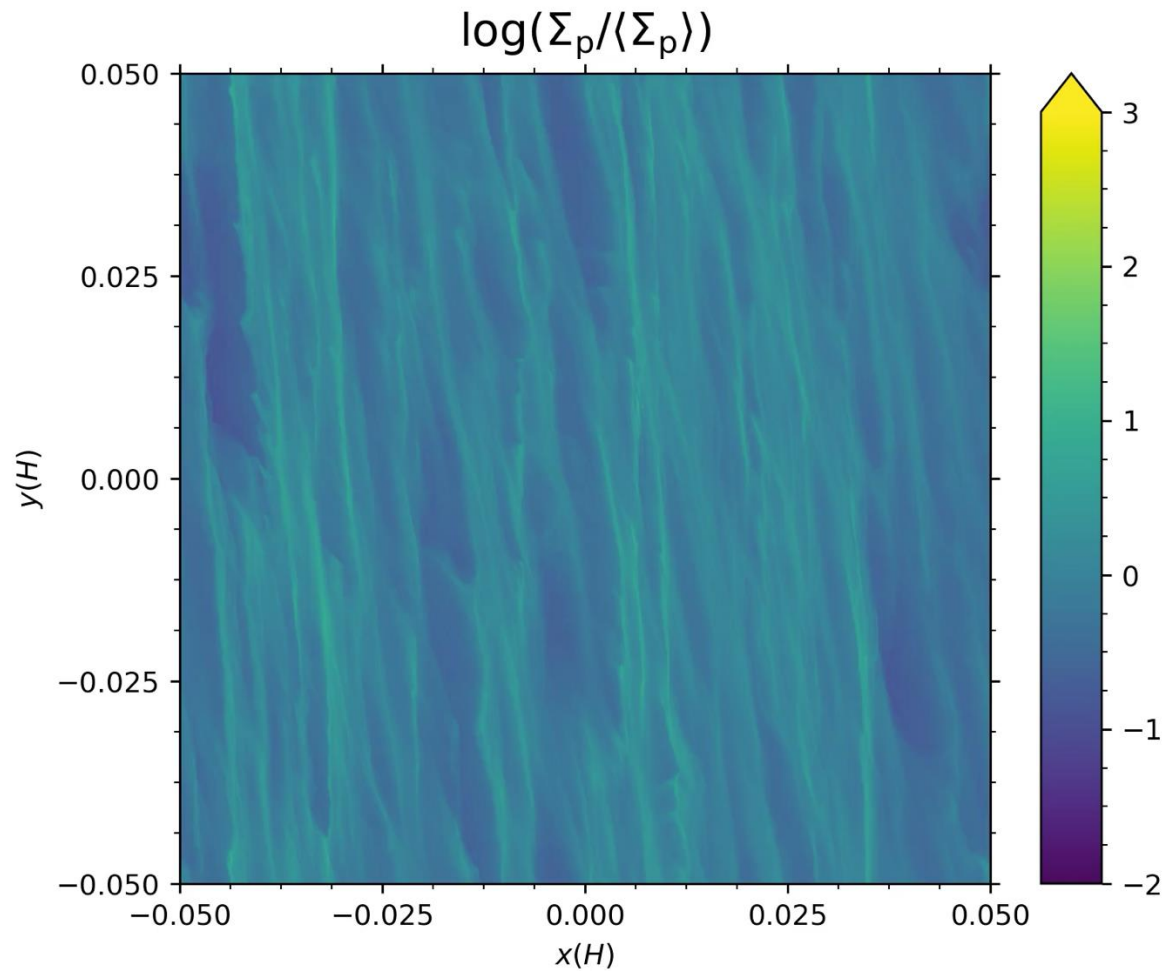
**How can the
streaming instability
hypothesis be verified?**

Kuiper Belt Cold Classical Binaries : Preference for Prograde

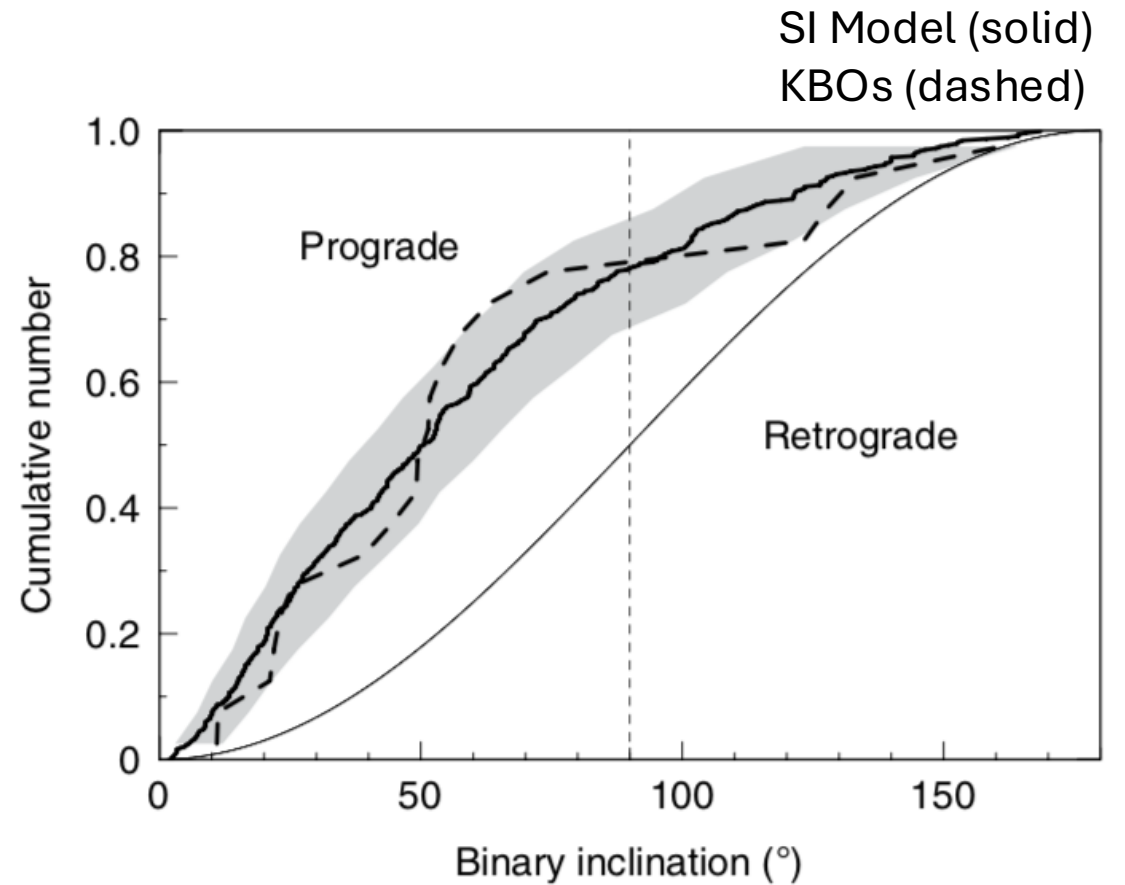


Grundy+2019

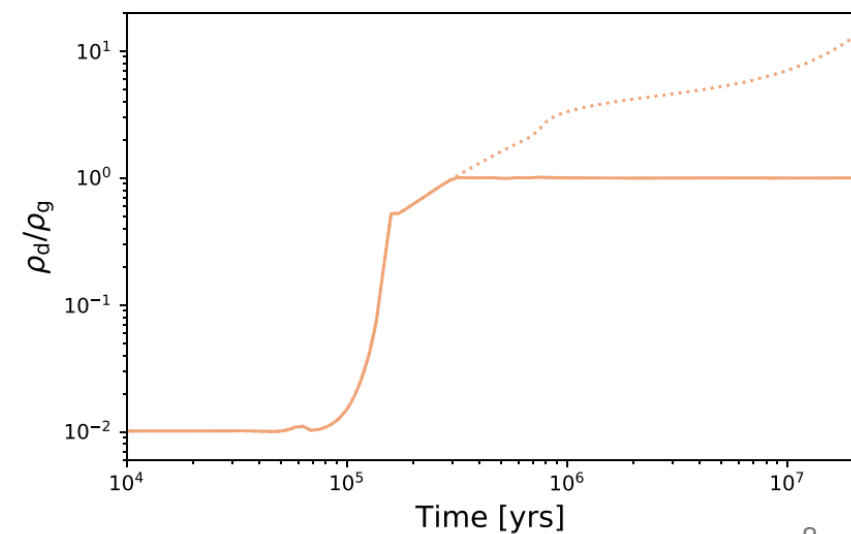
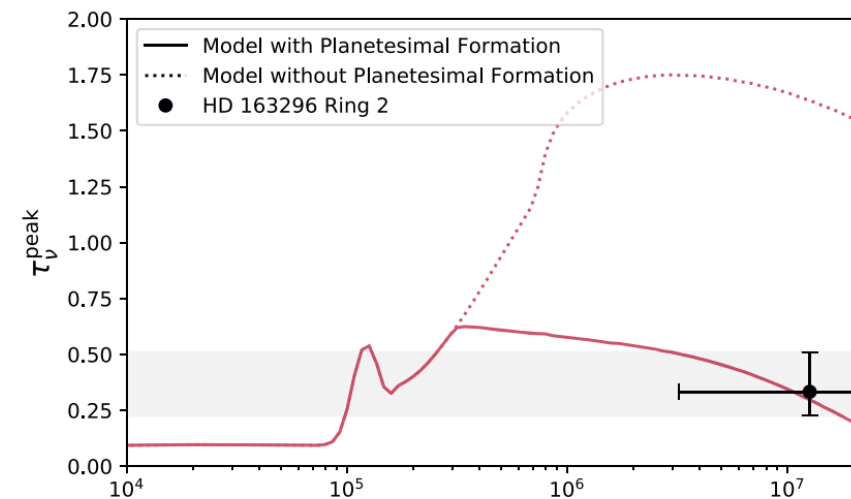
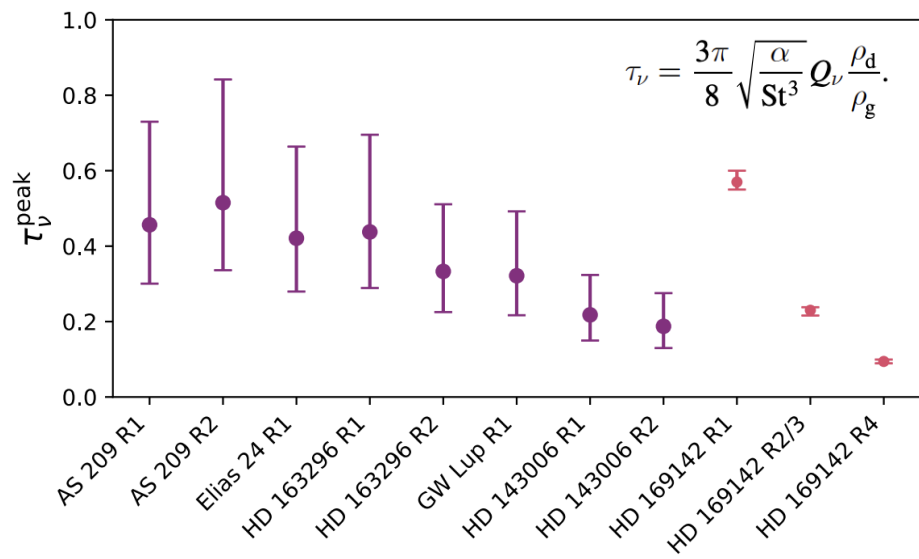
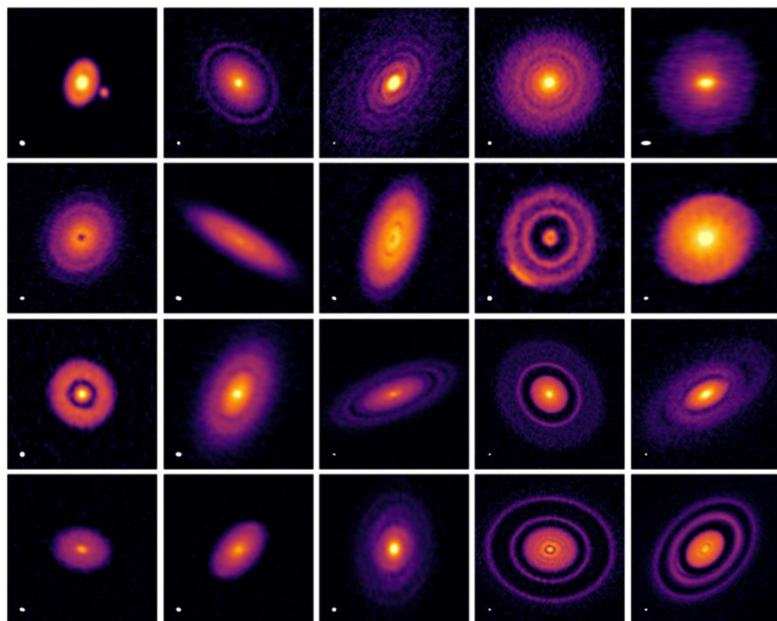
Counting binaries: Preference for Prograde (~80%)



Video credit: Rixin Li



Evidence for streaming instability? Protoplanetary disks

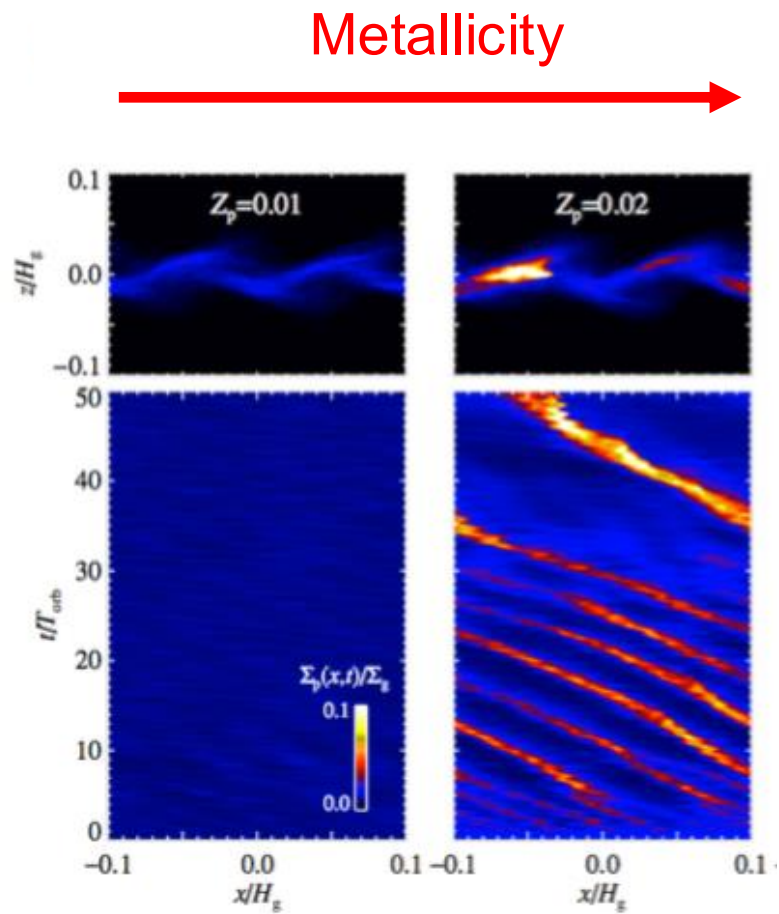


Stammler et al. (2022)

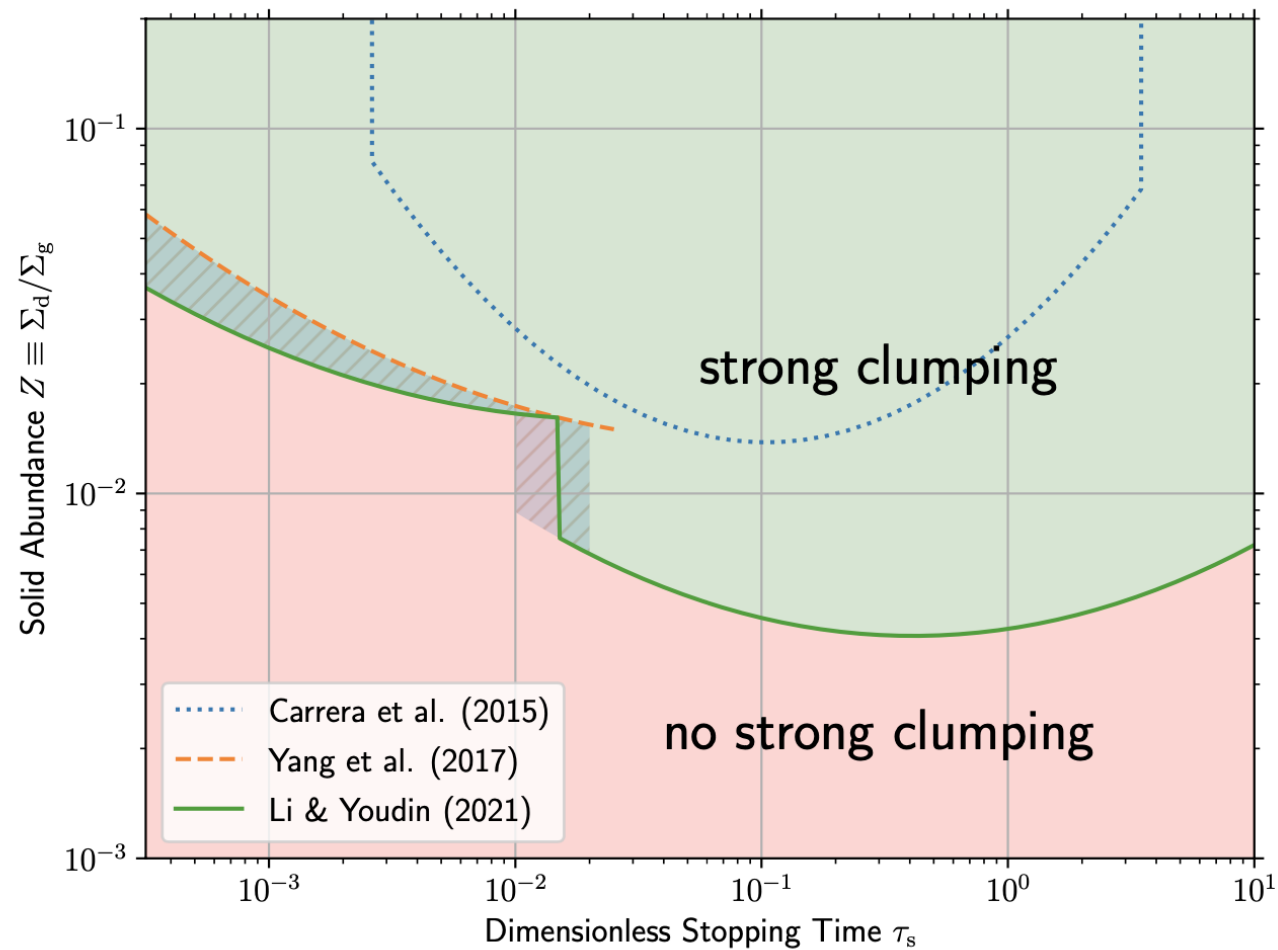
Open Questions on Streaming Instability

- Numerical convergence
- Clumping boundary
- What is happening sub-grid scale?
- Formation at special locations vs continuous area
- Can we observe the filaments?

Metallicity threshold?

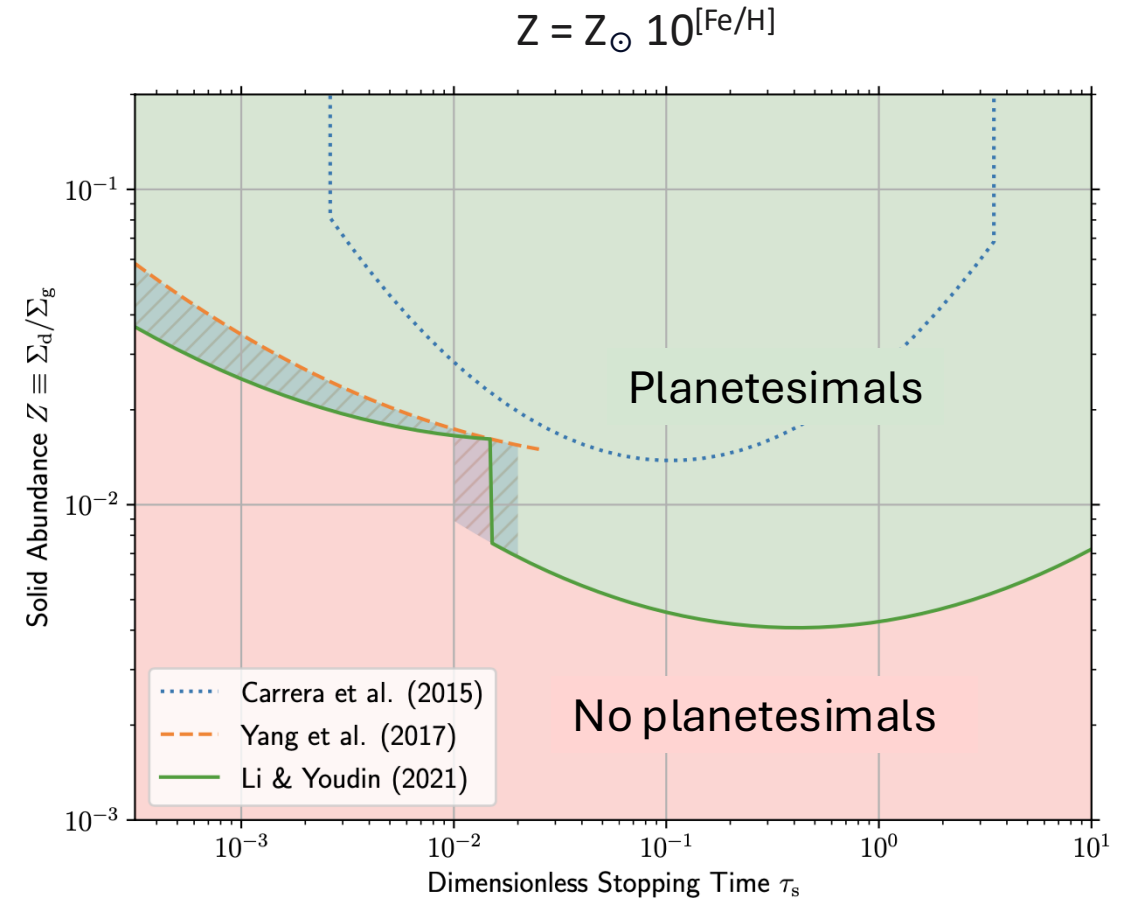
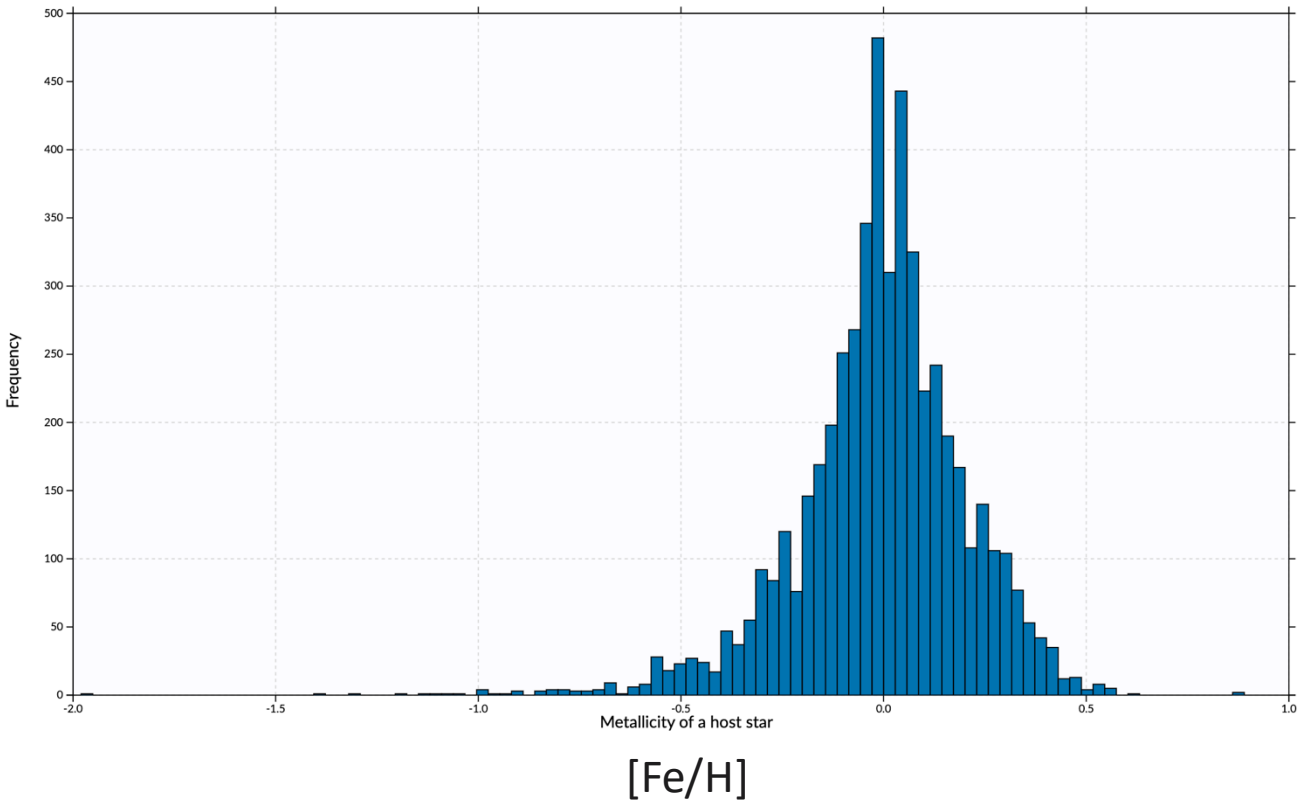


Johansen et al. (2011)

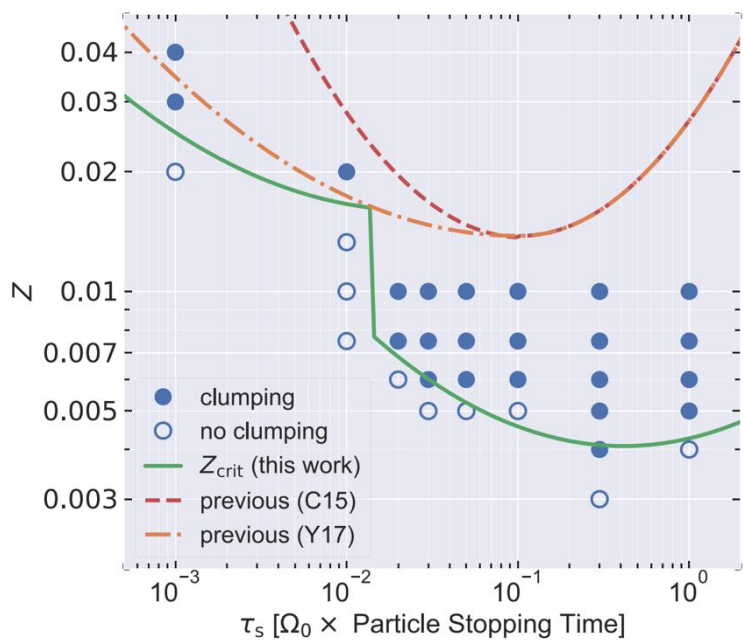


Lesur et al. 2023

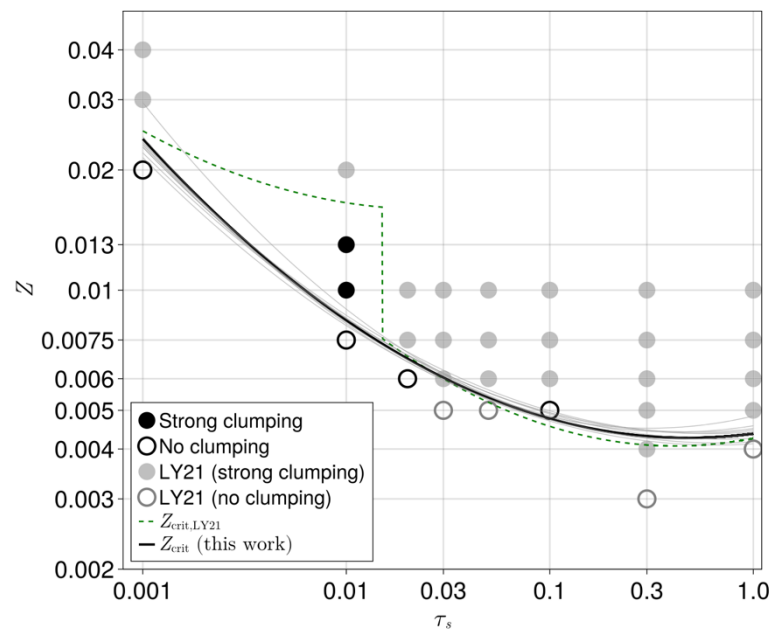
Metallicity threshold?



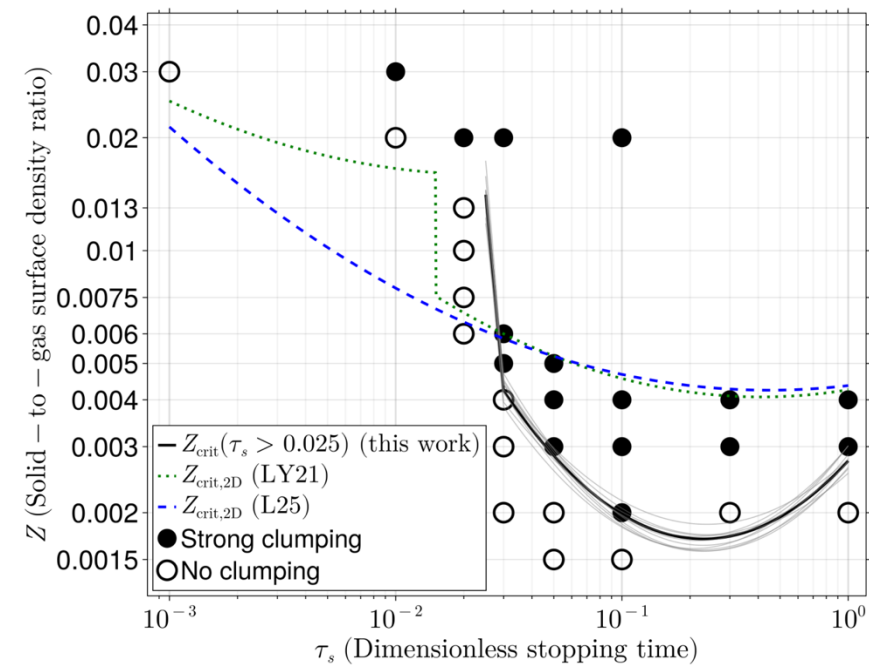
Clumping Threshold Problem



Li & Youdin 2021



Lim et al. 2024



Lim et al. 2025

Numerics? Are the codes agreeing?

DRAFT VERSION APRIL 7, 2026
Typeset using L^AT_EX twocolumn style in AASTeX7.0.1

A Comparative Study of the Streaming Instability: Unstratified Models with Marginally Coupled Grains

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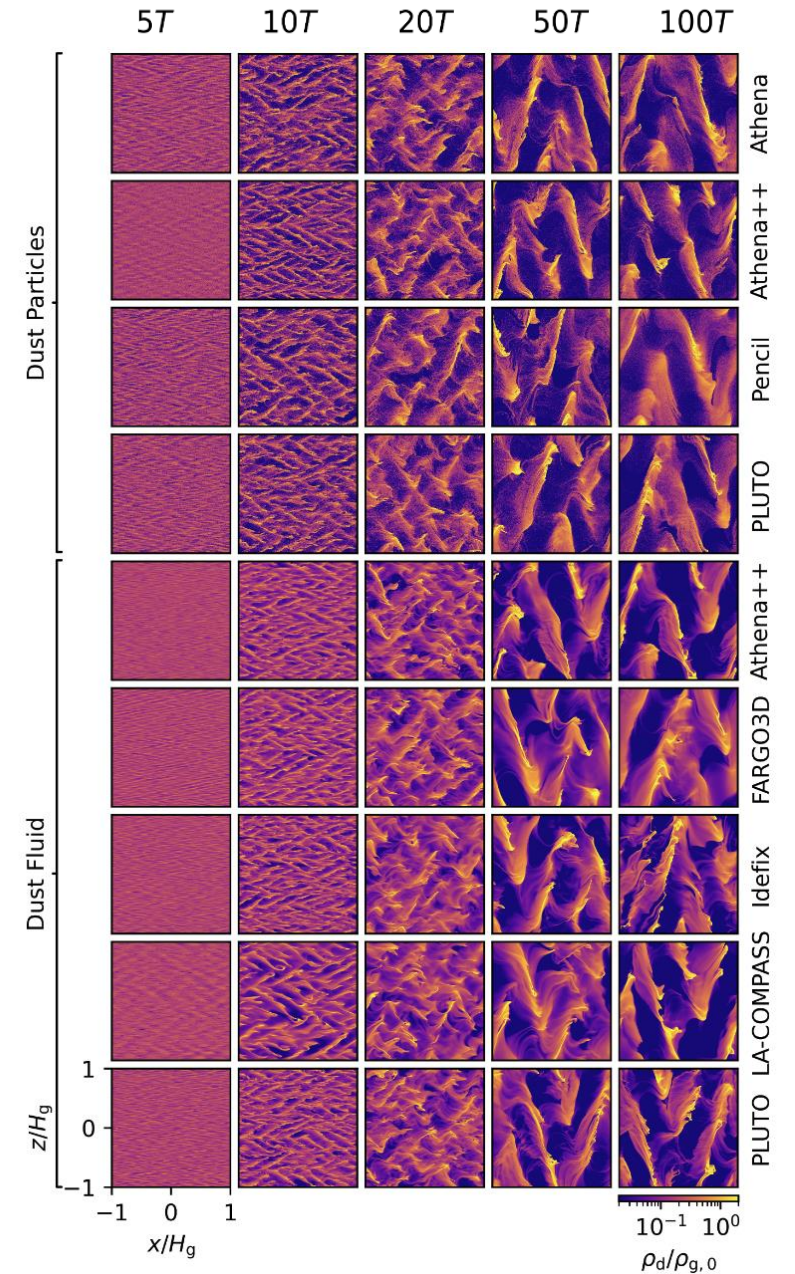
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ABSTRACT

The streaming instability is a leading mechanism for concentrating solids and initiating planetesimal



[astro-ph.EP] 4 Apr 2026

Problem: Run BA

- Johansen & Youdin (2007)
 - (Stokes number) $\tau_s \equiv \Omega_K t_s = 1$
 - Dust-to-gas ratio $\epsilon \equiv \frac{\langle \rho_p \rangle}{\rho_{g,0}} = 0.2$
- Grid resolutions
 - 512^2
 - $n_p = 1, 9$ ($> 260K$, 2.3M particles)
 - 1024^2
 - $n_p = 1$ ($> 1M$ particles)

TABLE 1
 RUN PARAMETERS

Run	τ_s	ϵ	$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$	N_p	Δt
AA.....	0.1	0.2	$4.0 \times 4.0 \times 4.0$	$256 \times 1 \times 256$	...	2000.0
AB.....	0.1	1.0	$2.0 \times 2.0 \times 2.0$	$256 \times 1 \times 256$	1.6×10^6	50.0
AC.....	0.1	3.0	$2.0 \times 2.0 \times 2.0$	$256 \times 1 \times 256$	1.6×10^6	50.0
BA.....	1.0	0.2	$40.0 \times 40.0 \times 40.0$	$256 \times 1 \times 256$	1.6×10^6	500.0
BB.....	1.0	1.0	$20.0 \times 20.0 \times 20.0$	$256 \times 1 \times 256$	1.6×10^6	250.0
BC.....	1.0	3.0	$20.0 \times 20.0 \times 20.0$	$256 \times 1 \times 256$	1.6×10^6	250.0
AB-3D.....	0.1	1.0	$2.0 \times 2.0 \times 2.0$	$128 \times 128 \times 128$	2.0×10^7	35.0
BA-3D.....	1.0	0.2	$40.0 \times 40.0 \times 40.0$	$128 \times 128 \times 128$	2.0×10^7	300.0

NOTE.—Columns give, from left to right, name of run, friction time, solids-to-gas ratio, box size in units of ηr , grid resolution, number of particles, and total run time in units of Ω^{-1} .

PROTOPLANETARY DISK TURBULENCE DRIVEN BY THE STREAMING INSTABILITY: NONLINEAR SATURATION AND PARTICLE CONCENTRATION

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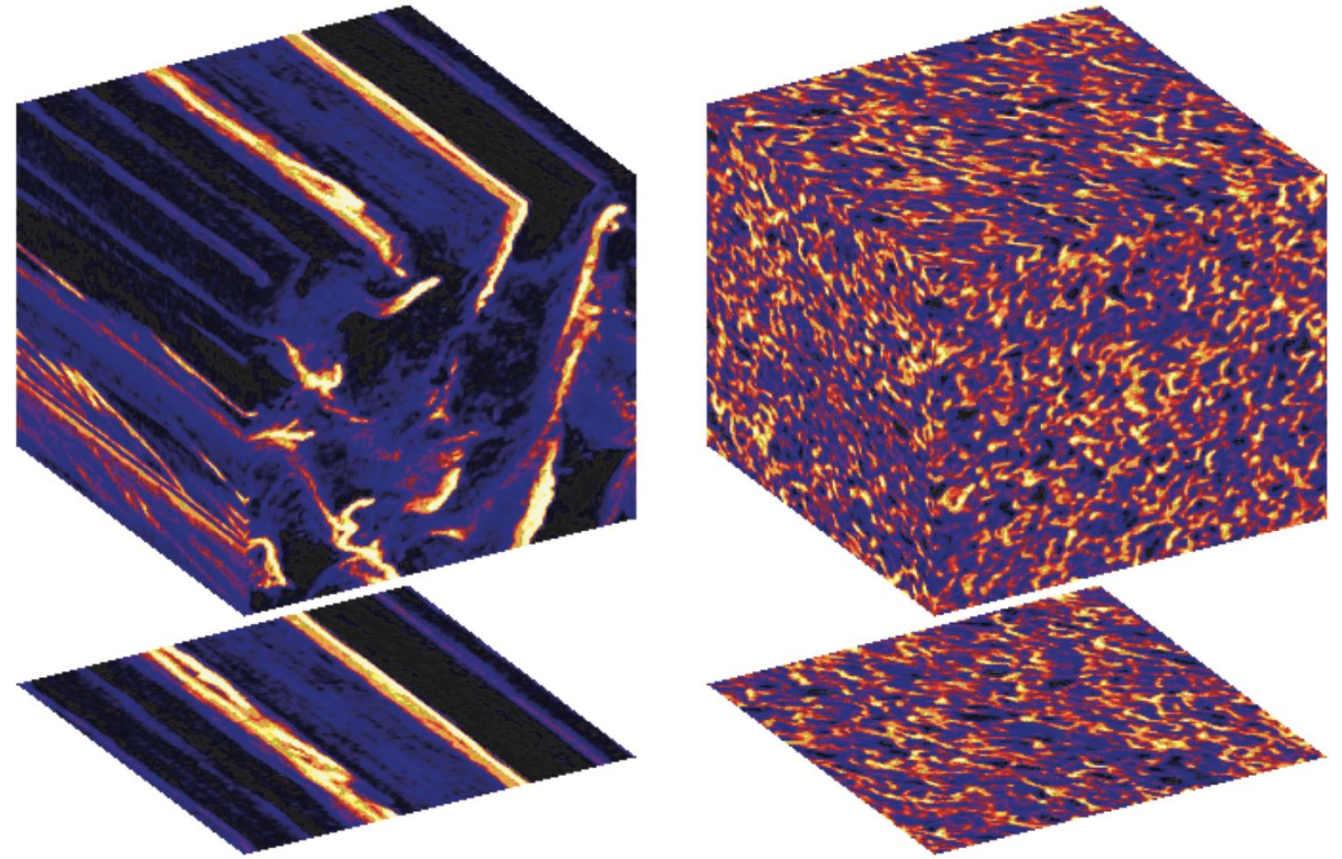
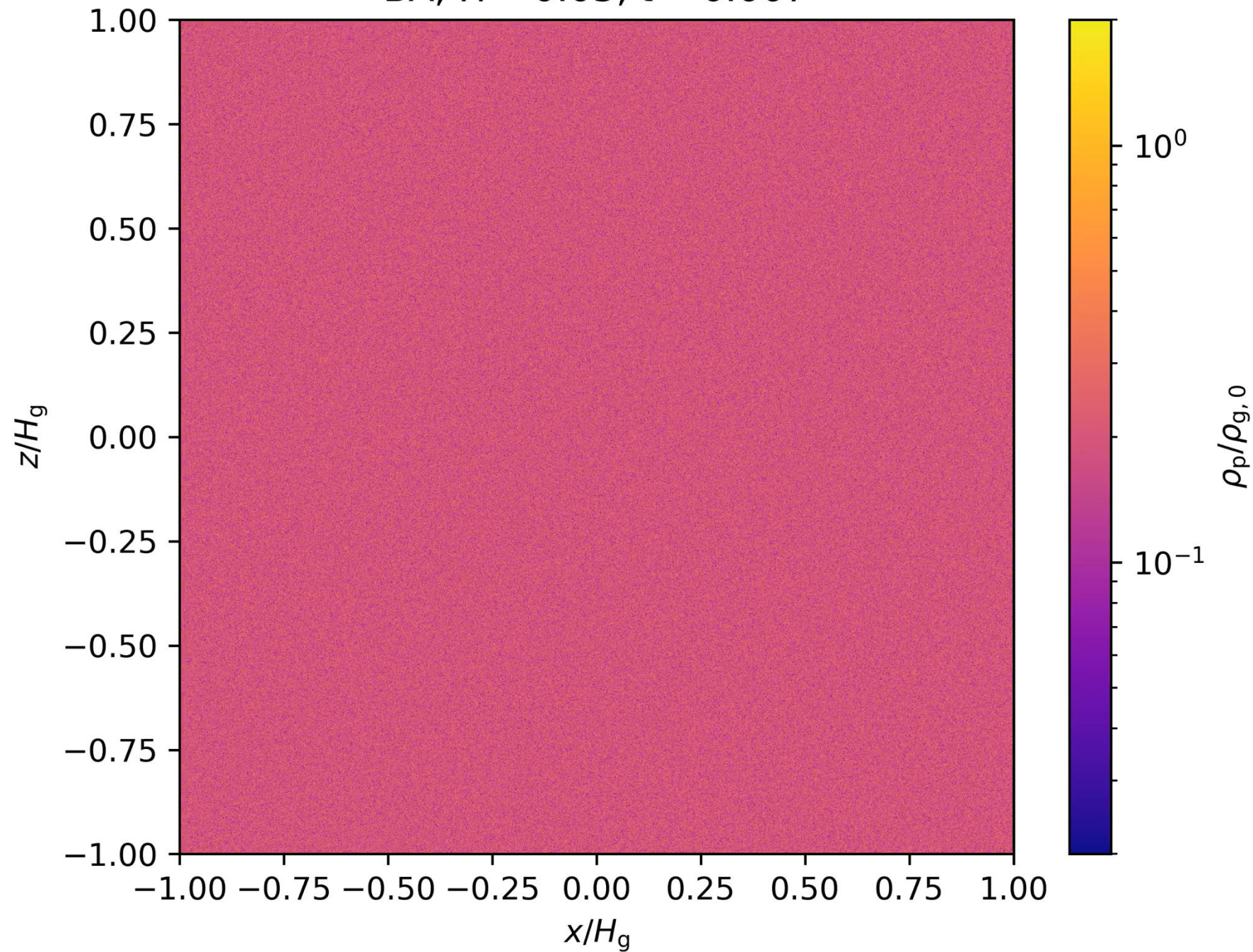


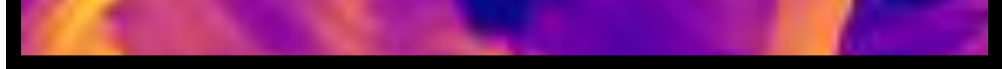
FIG. 9.—Saturated streaming turbulence for run BA-3D ($\epsilon = 0.2$, $\tau_s = 1.0$, left) and run AB-3D ($\epsilon = 1.0$, $\tau_s = 0.1$, right). The boxes are oriented with the radial x -axis to the right and slightly up, the azimuthal y -axis to the left and up, and the vertical z -axis directly up. The contours show the particle density at the sides of the simulation box after the streaming turbulence has saturated. The axisymmetry of the marginally coupled particles witnesses the smearing effect of Keplerian shear on the relatively long-lived clumps. The tightly coupled particles drive rapid fluctuations that develop fully nonaxisymmetric density patterns. [This figure is available as an mpeg animation in the electronic edition of the Journal.]



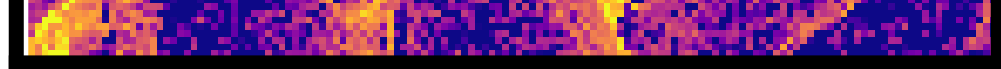
Codes and Numerical Methods

Table 2. Codes

Code (1)	Section (2)	Dust (3)	Equations (4)	Riemann Solver		Reconstruction		Time	
				Gas (5)	Dust (6)	Gas (7)	Dust (8)	Integrator (9)	Order (10)
Athena	2.2.2	Particles ^a	(2), (14)	HLLC ^c	...	PPM ^h	...	CTU ^m	2nd
Athena++	2.2.3	Particles	(7), (15), (16)	HLLE ^d	...	PPM ⁱ	...	VL2 ⁿ	2nd
		Fluid ^b	(2), (21)	Roe ^e	Custom ^f	PPM	PLM	VL2	2nd
Idefix	2.2.5	Fluid	(2), (21)	HLLC	HLL	PLM ^j -VLFL ^k	PLM-VLFL	TVD ^o -RK2 ^p	2nd
LA-COMPASS	2.2.6	Fluid	(2), (21)	HLLE	HLLE	PLM	PLM	TR-BDF2 ^q	2nd
PLUTO	2.2.8	Particles	(2), (14)	Roe	...	PPM	...	RK2	2nd
		Fluid	(2), (21)	Roe	Exact ^g	PLM-MC ^l	PLM-MC	RK2	2nd
FARGO3D	2.2.4	Fluid	(2), (21)	...	...	PLM-VLFL	PLM-VLFL	Euler	1st
Pencil	2.2.7	Particles	(7), (15), (16)	...	...	...	...	RK4	4th

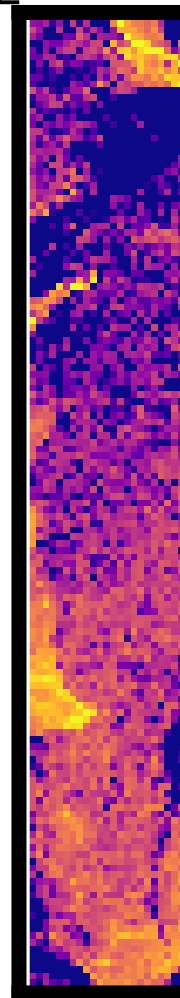
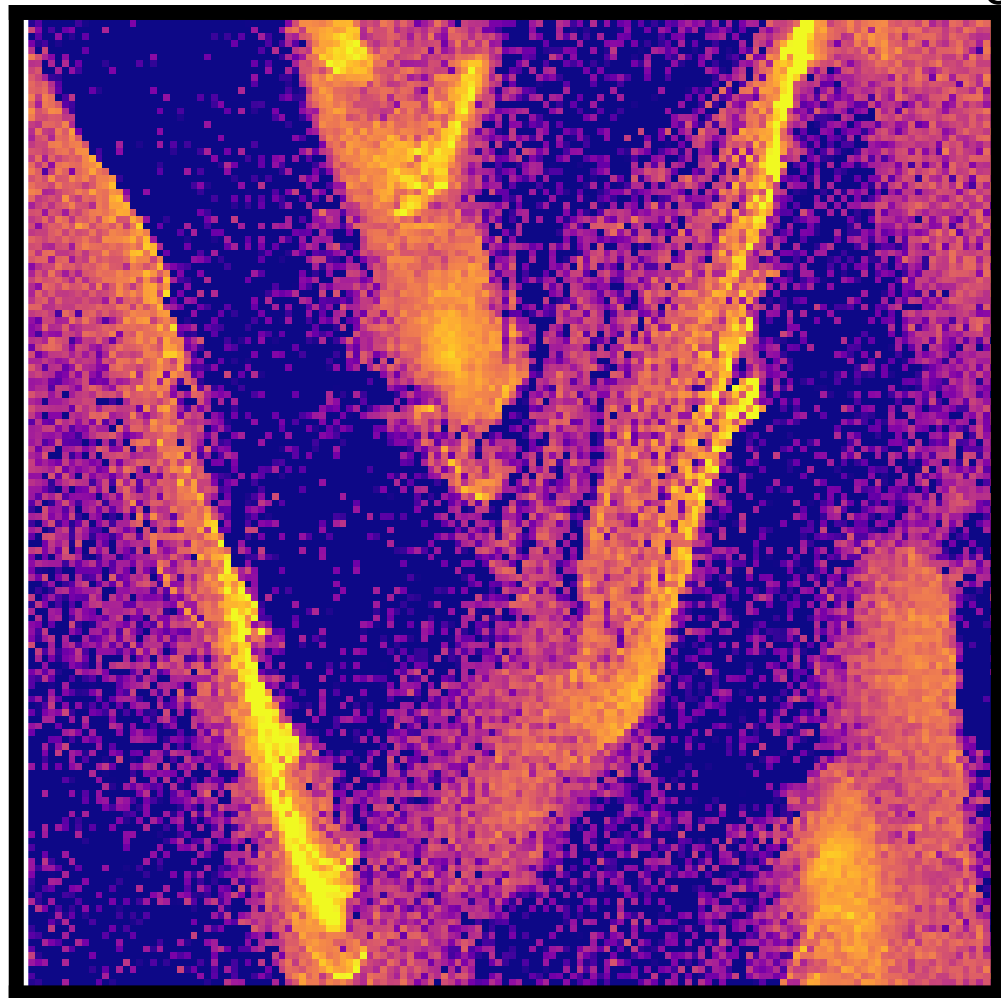
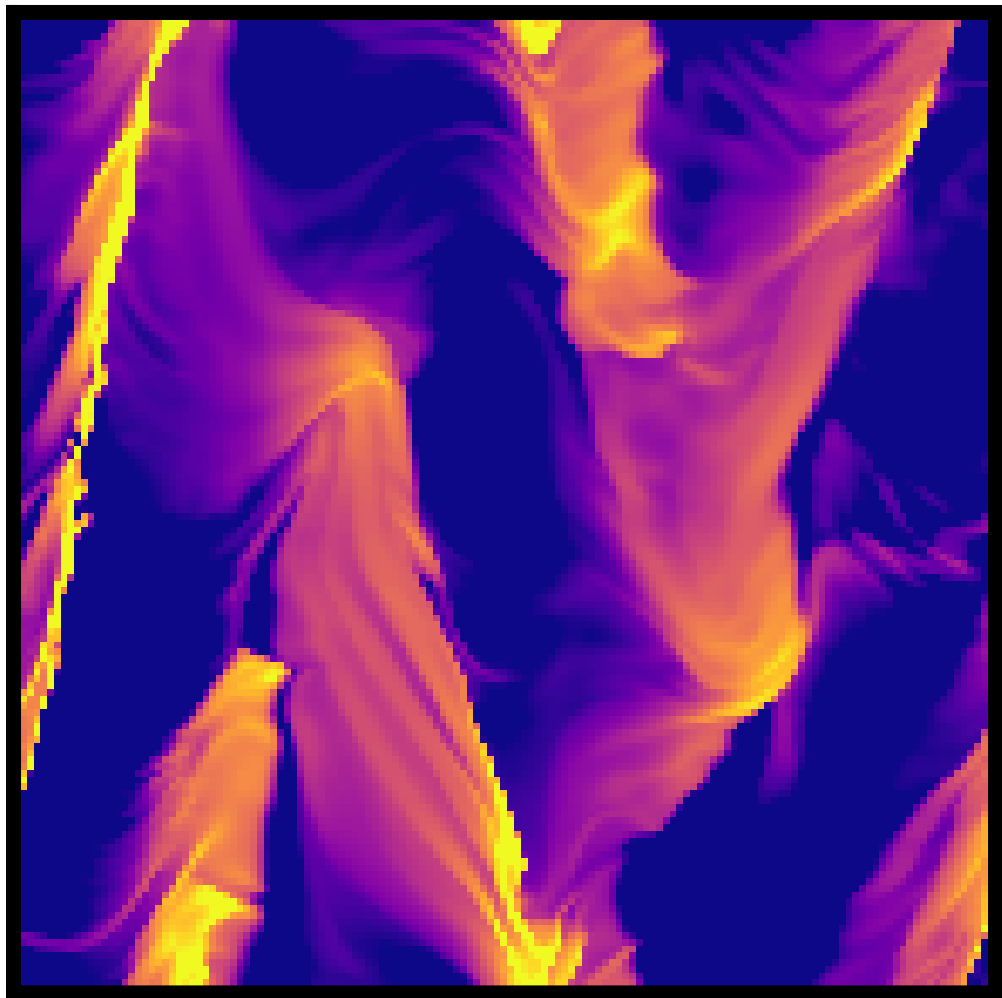
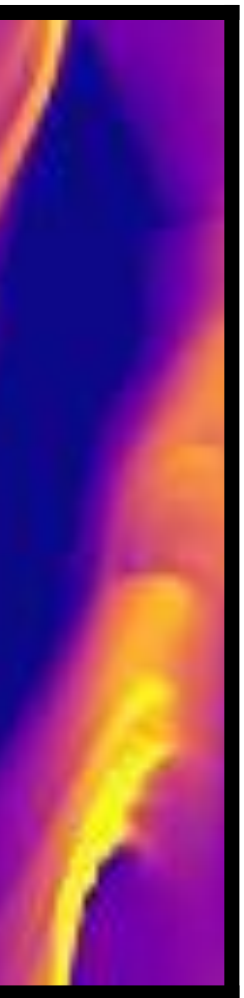


Dust Fluid



Dust Particles

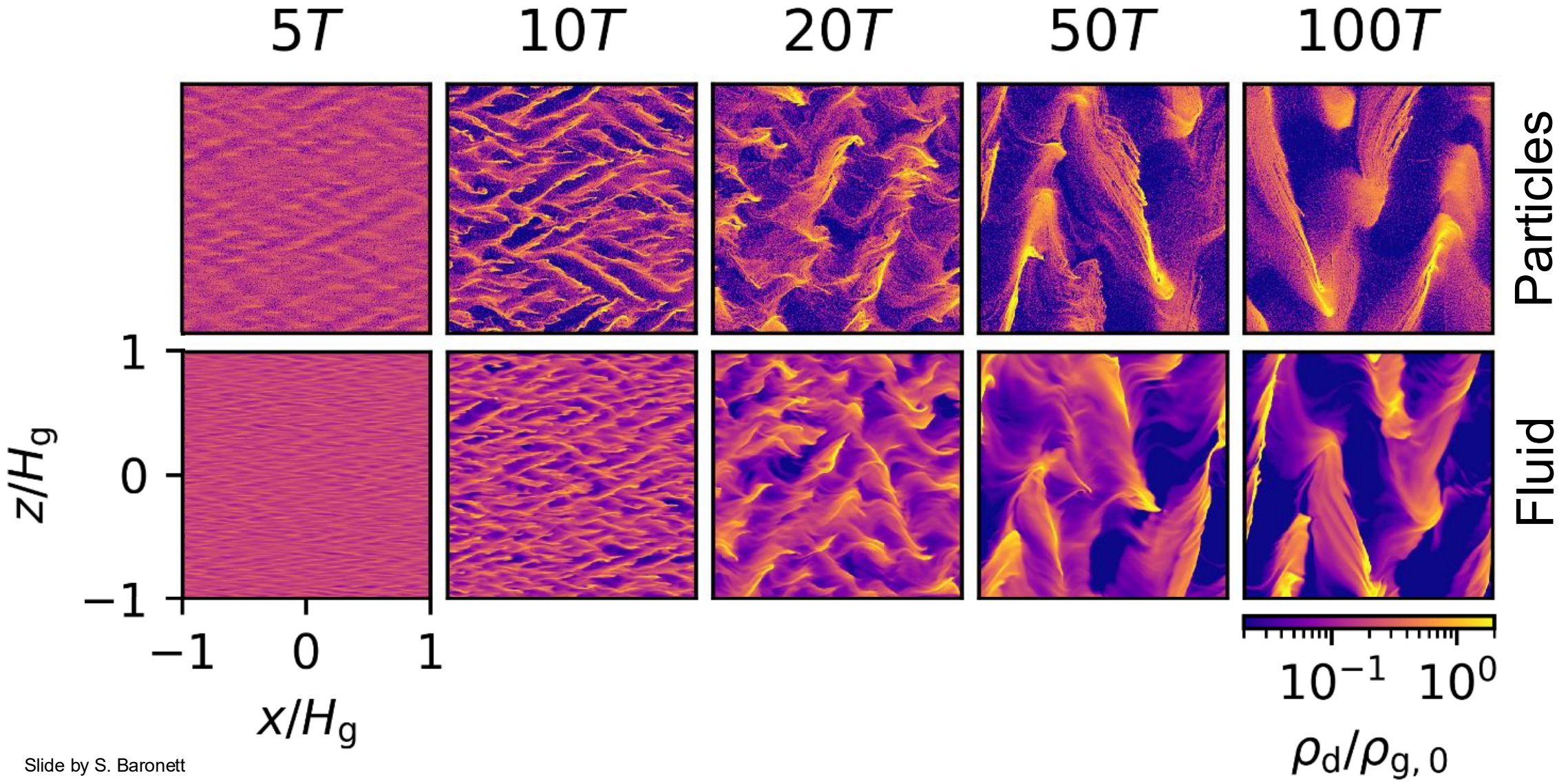
512²



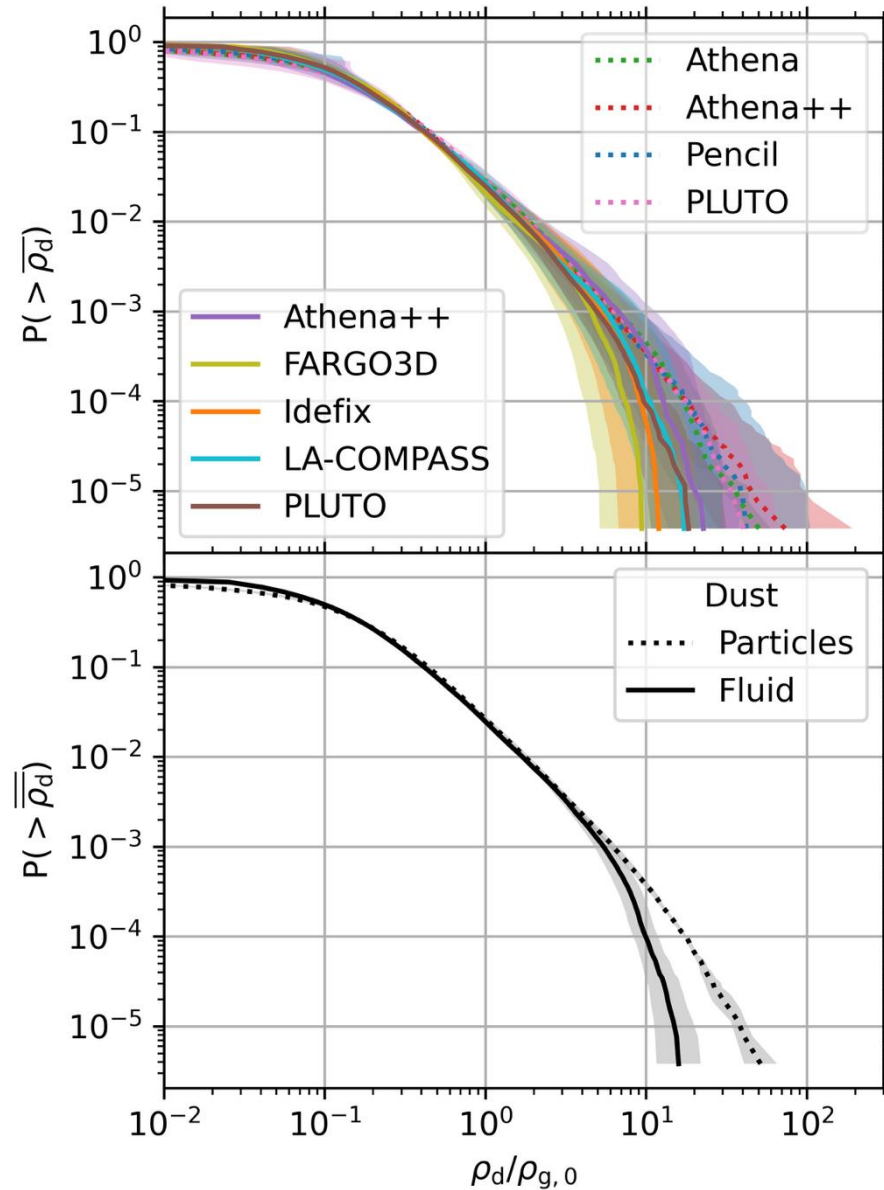
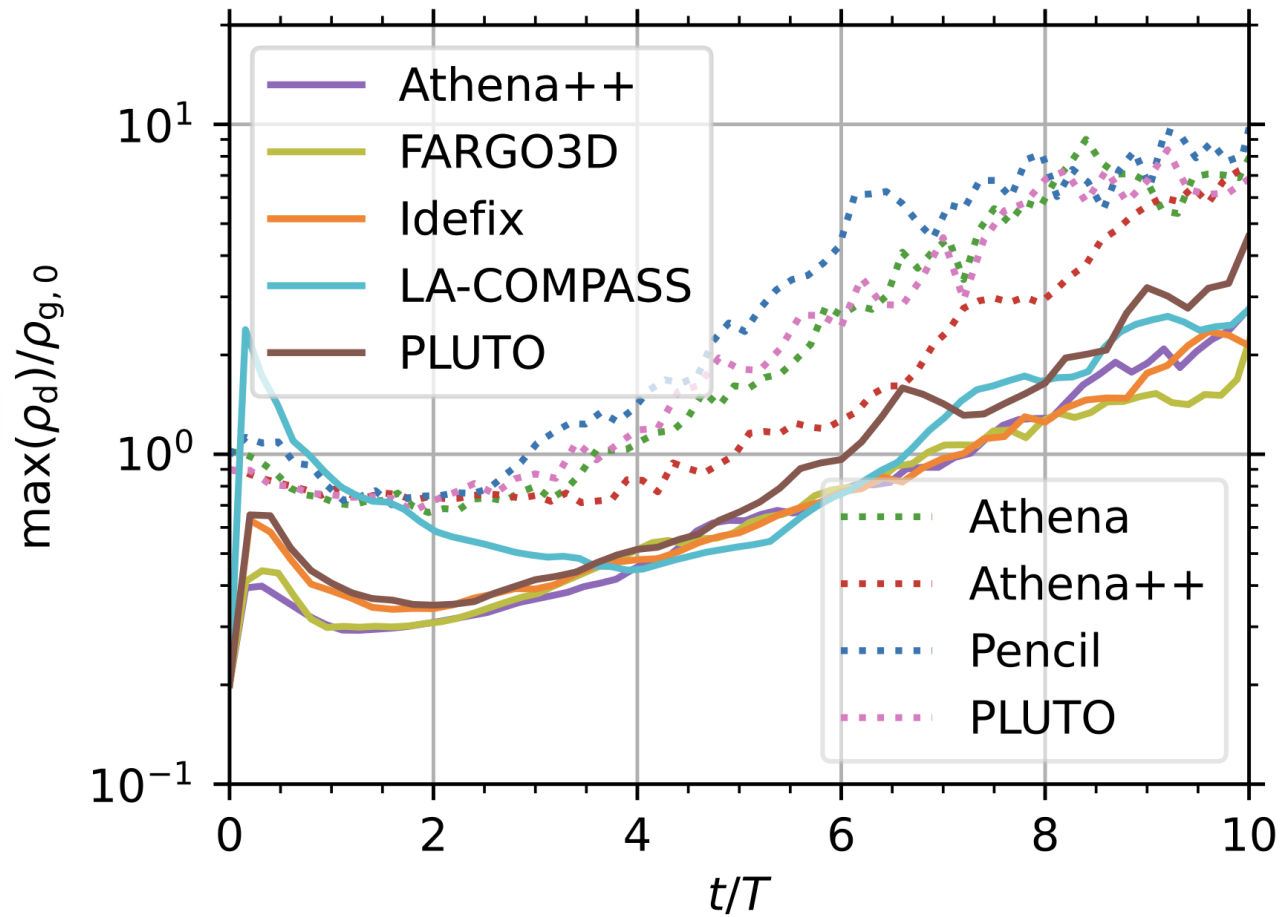
3D Athena++

PLUTO

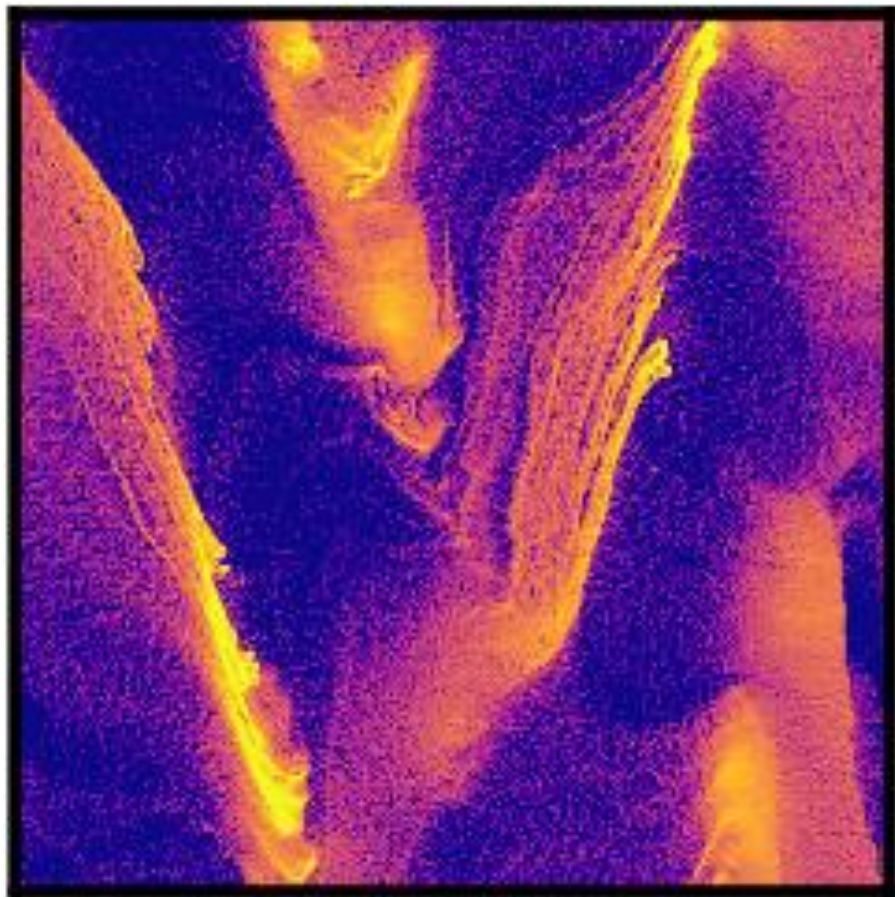
Athena++ (512² Fiducial Grid Resolution)



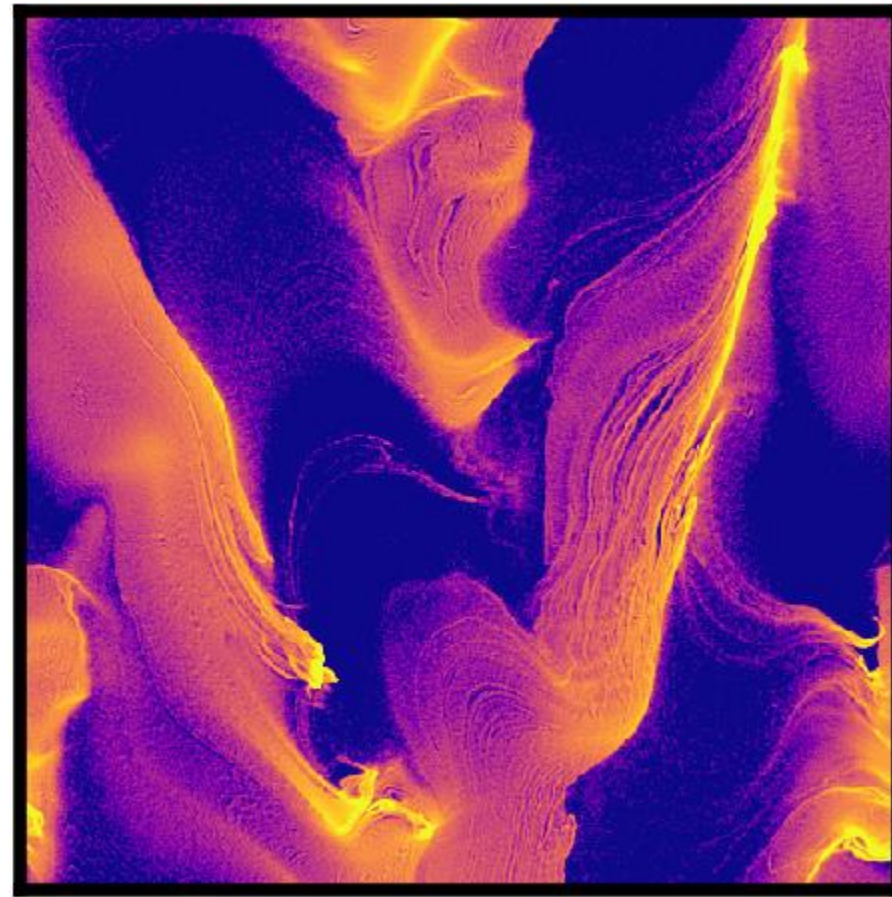
Fiducial Grid Resolution (512^2)



Higher Particle Resolution (512² grid): PLUTO

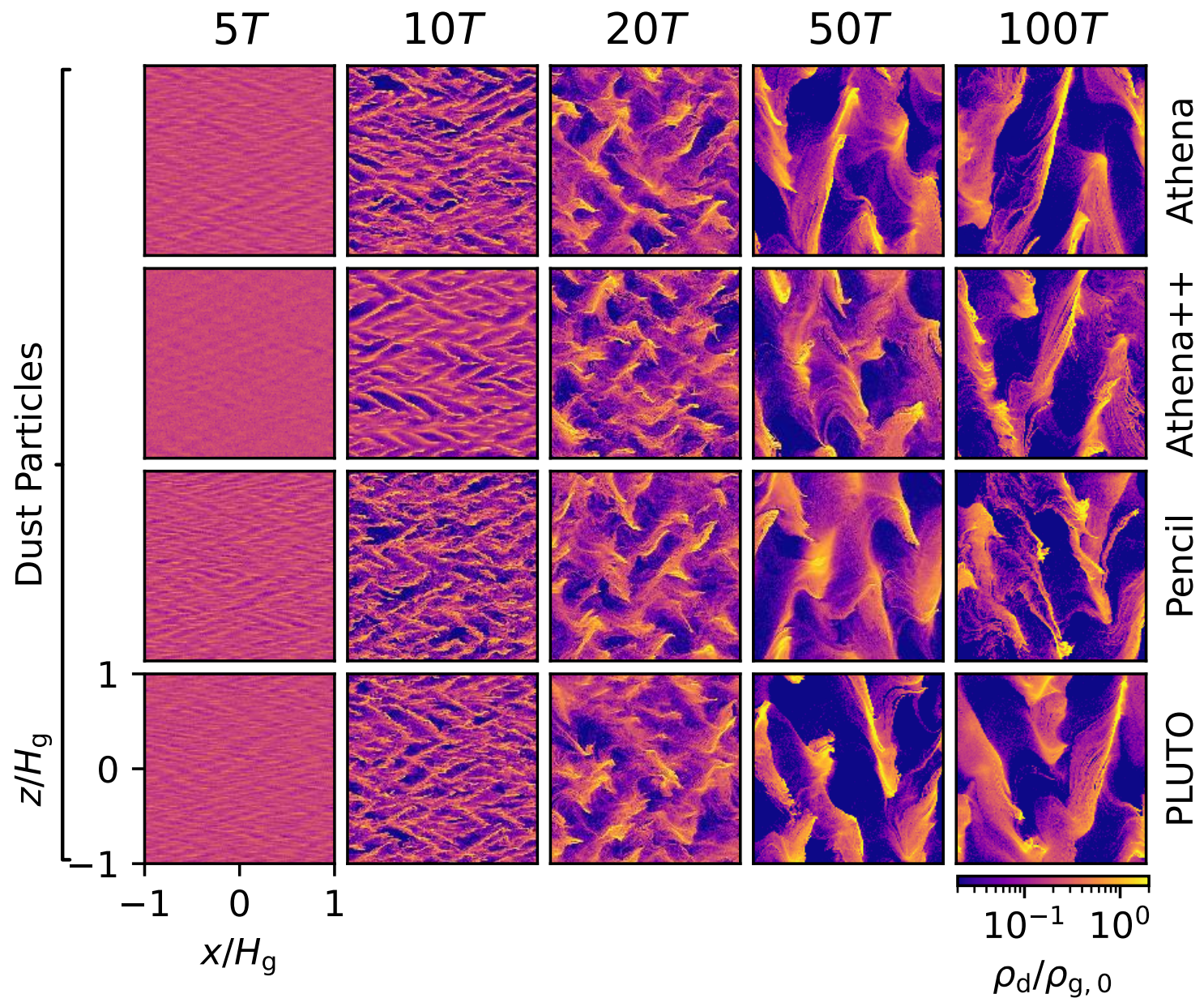


$$n_p = 1$$

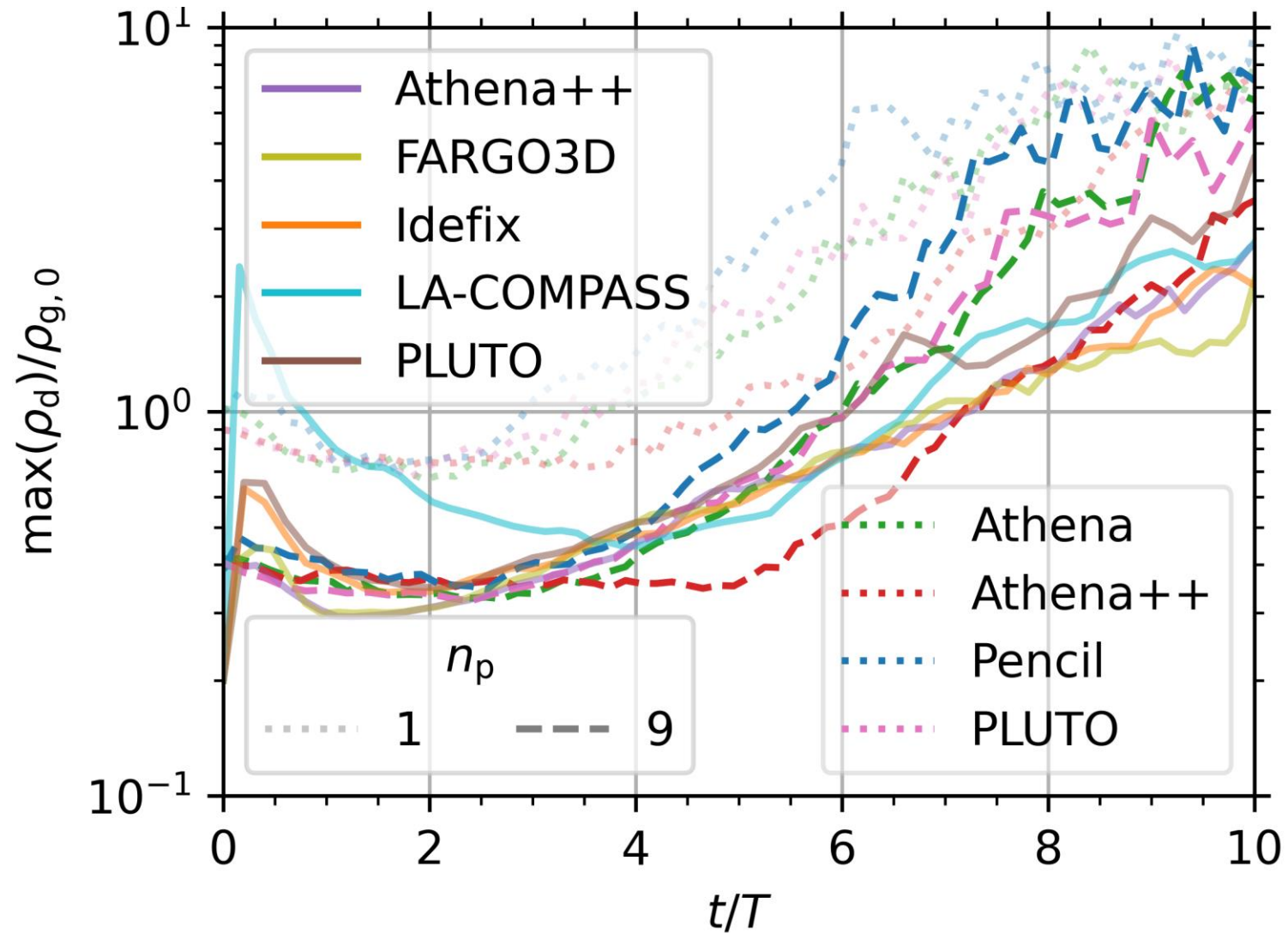


$$n_p = 9$$

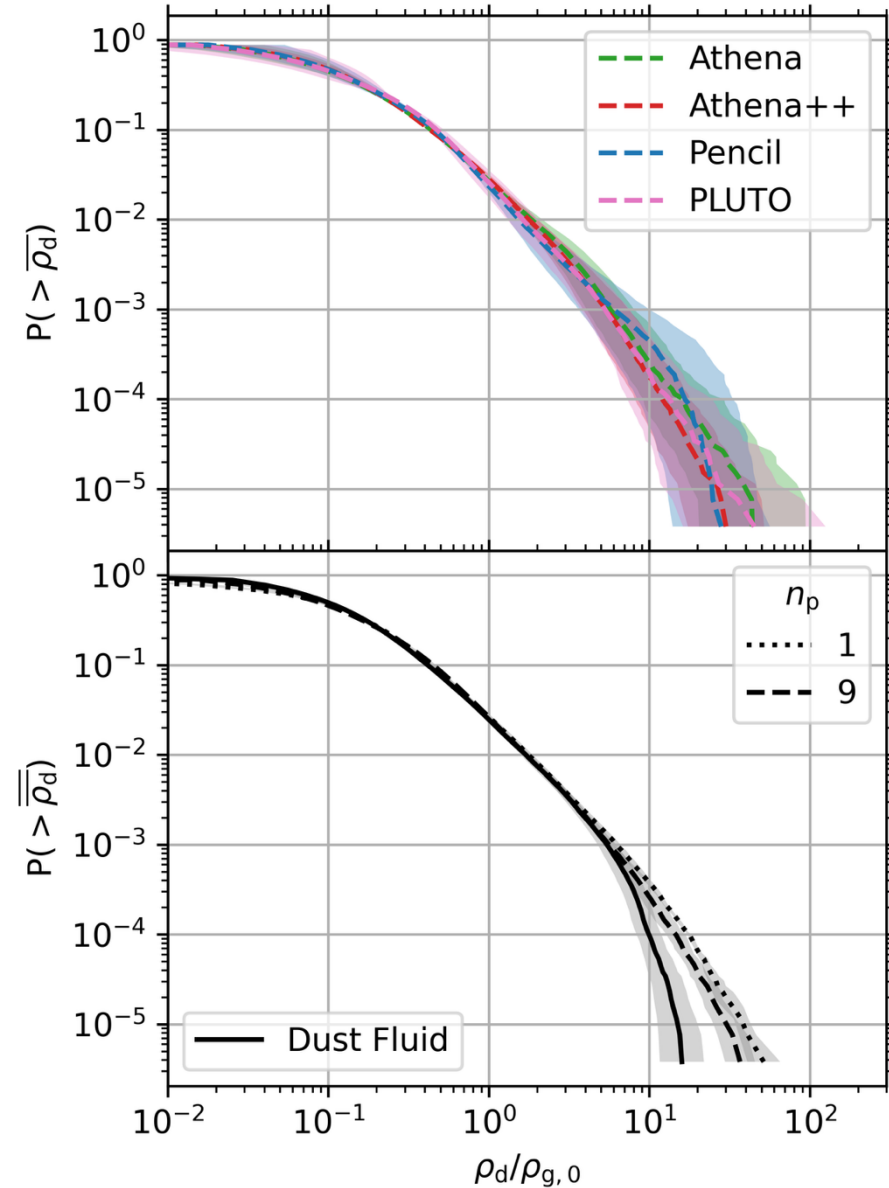
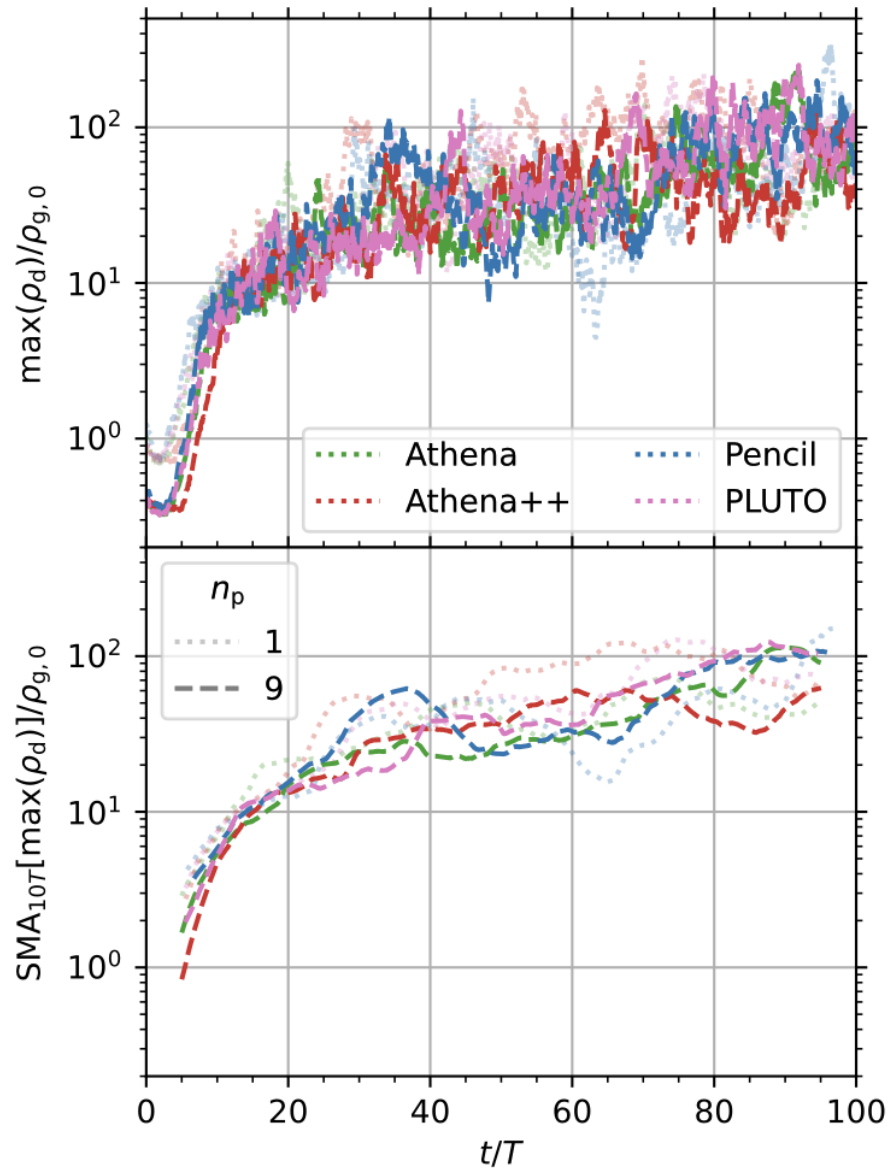
Higher Particle Resolution (512² grid)

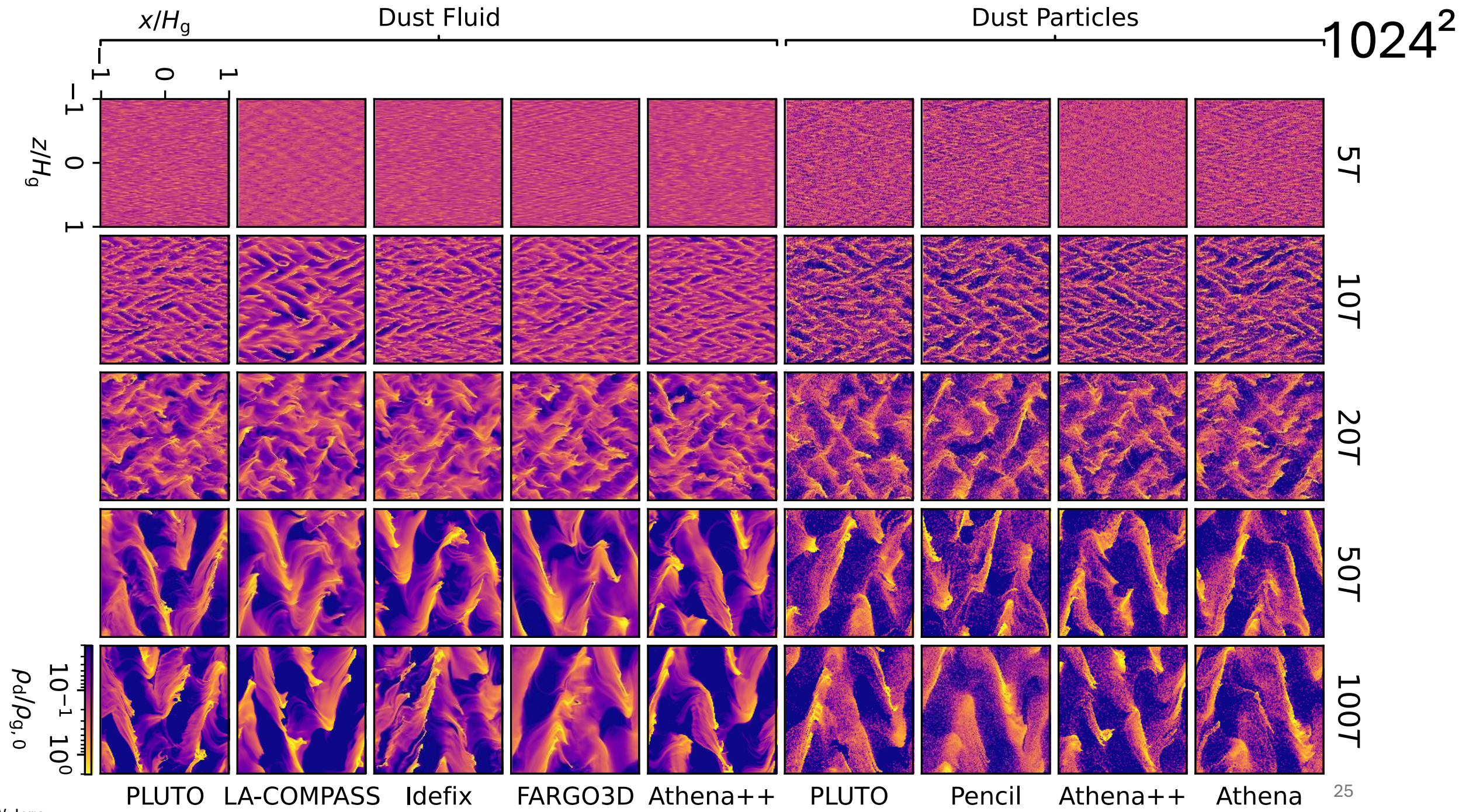


Higher Particle Resolution (512² grid)

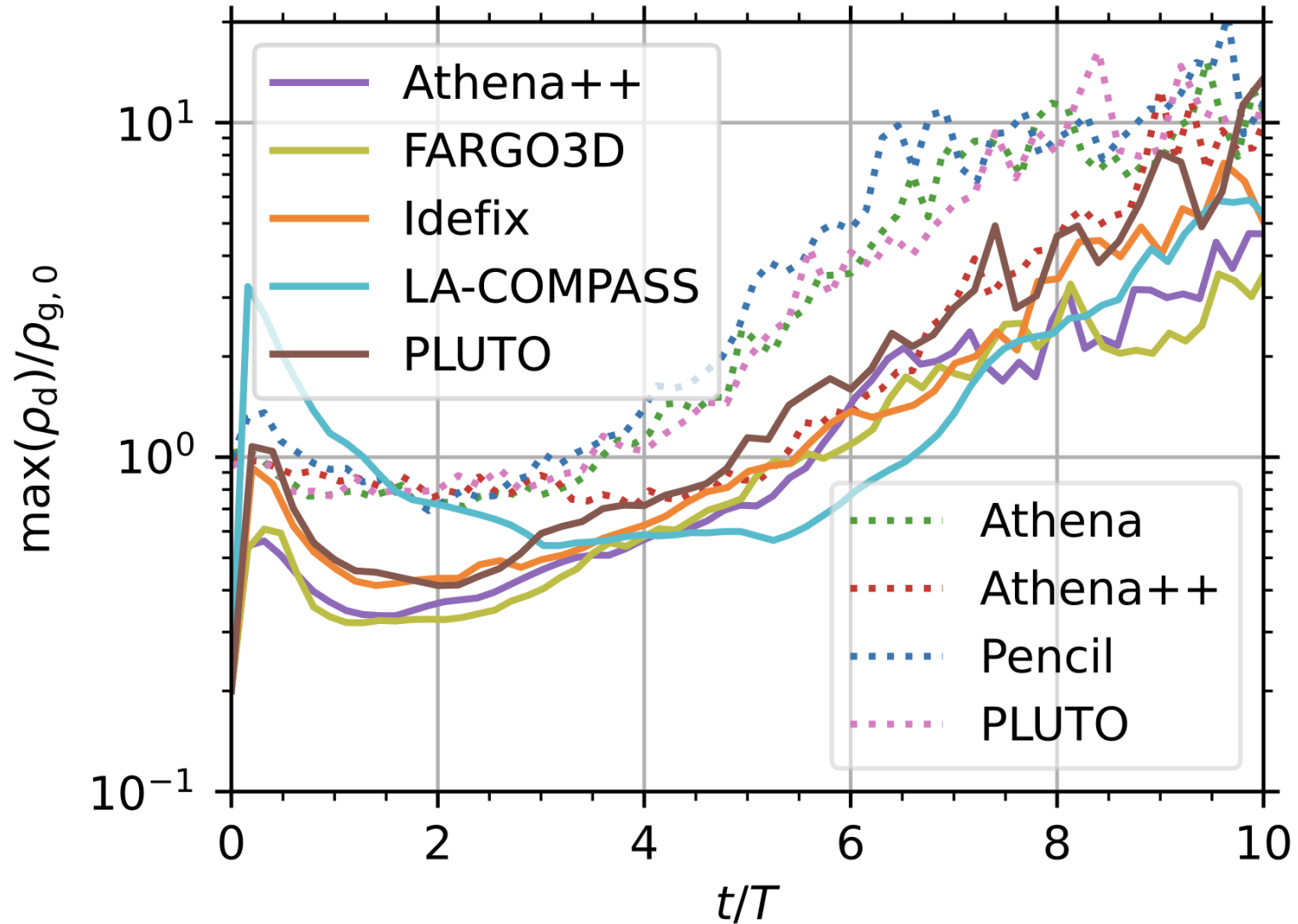


Higher Particle Resolution (512^2 grid)

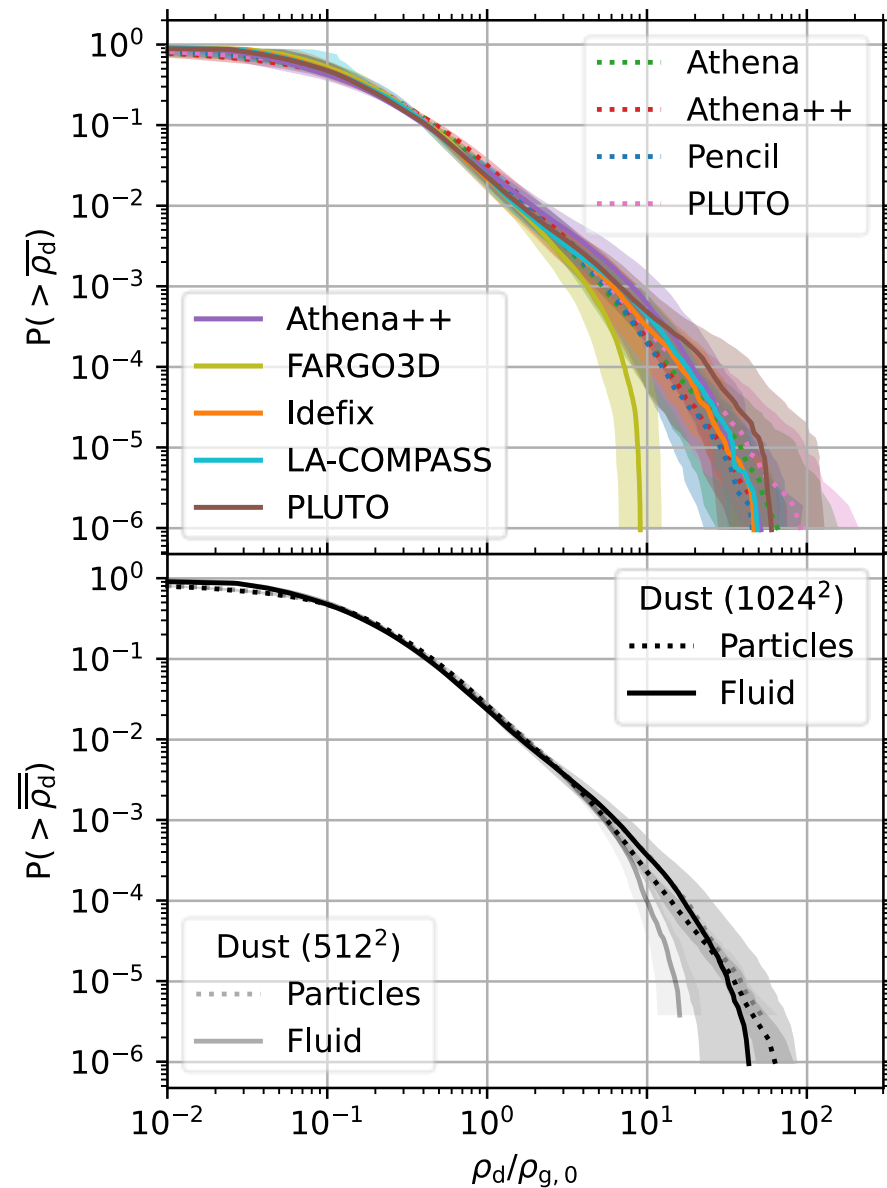
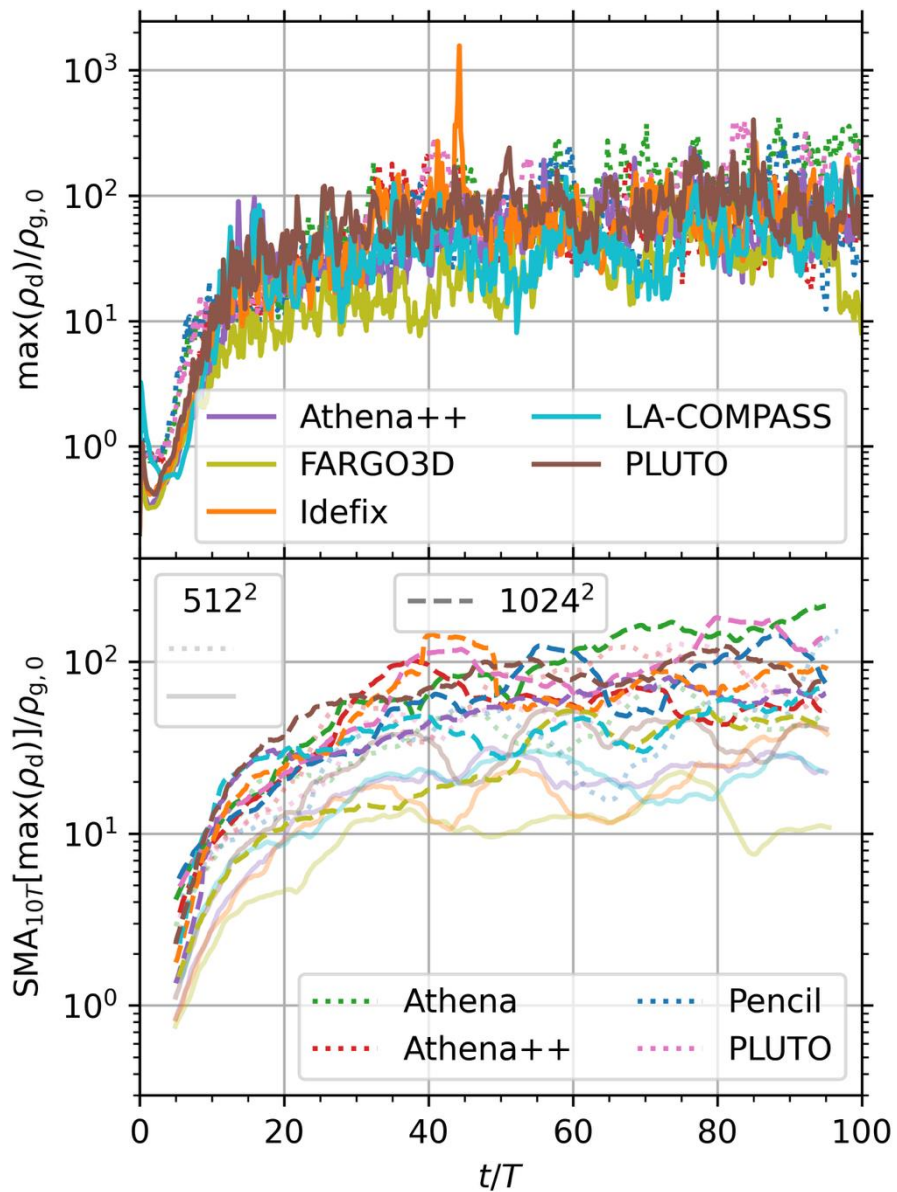




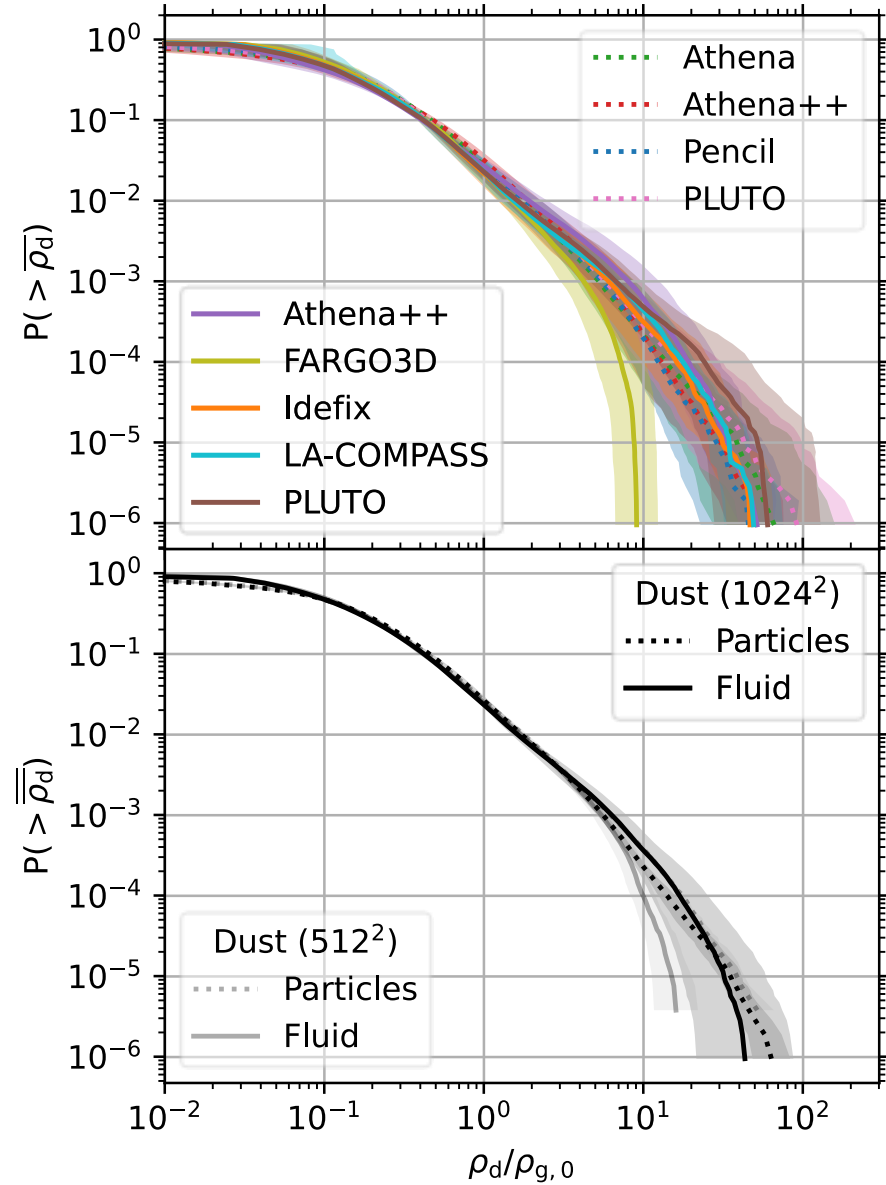
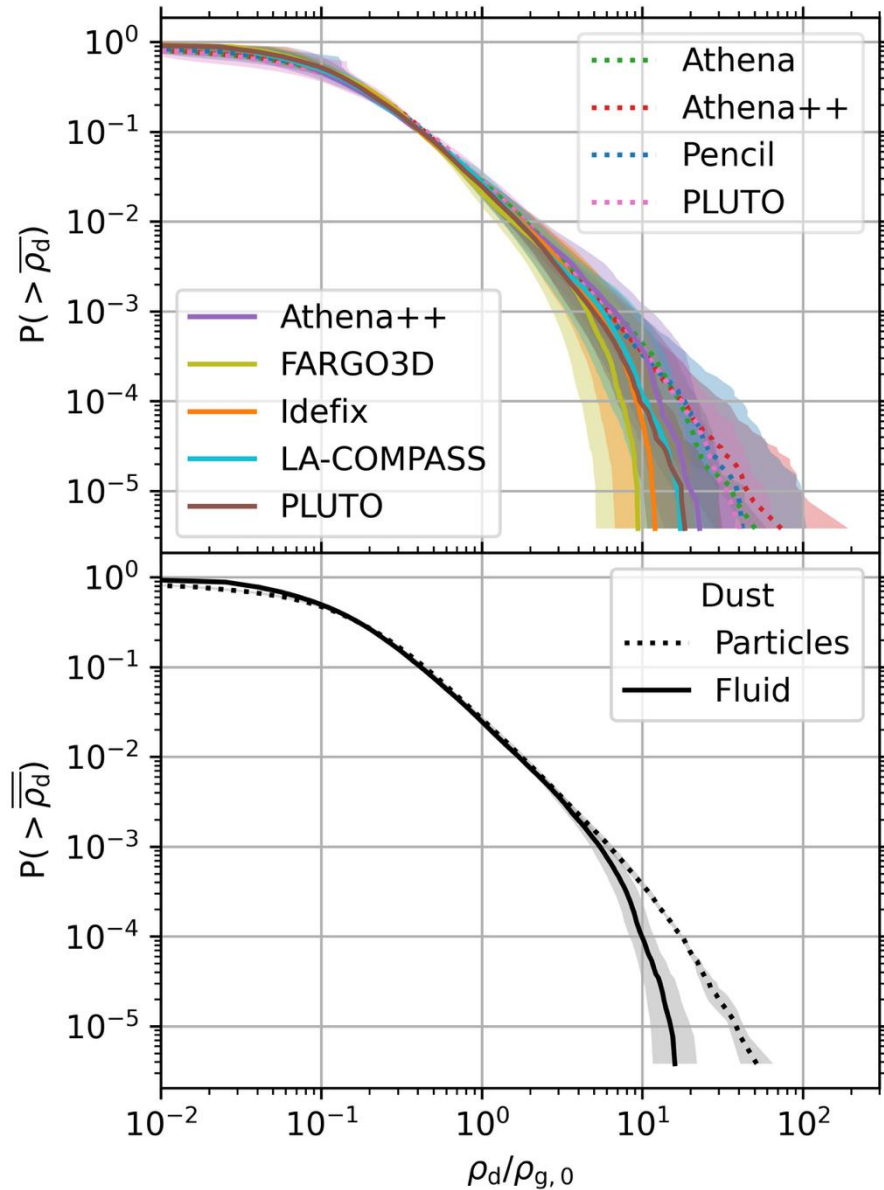
Higher Grid Resolution (1024^2)



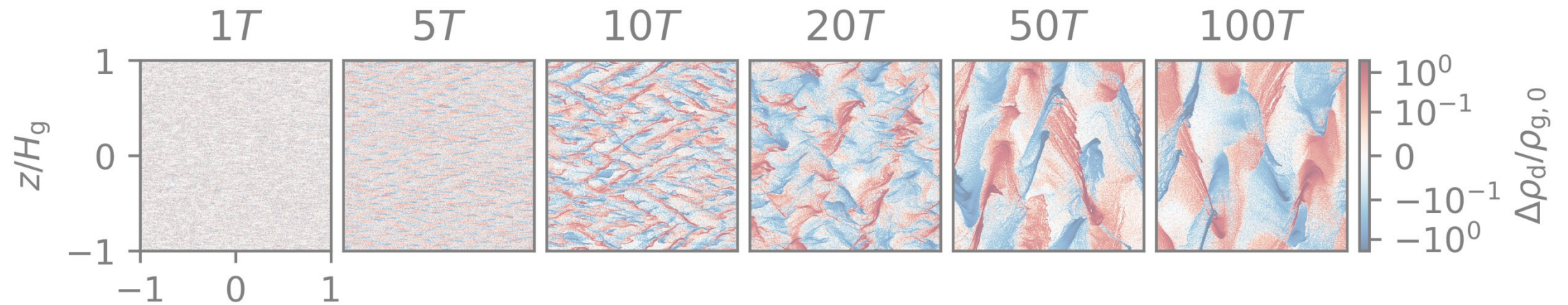
Higher Grid Resolution (1024²)



Higher Grid Resolution (512² - 1024²)



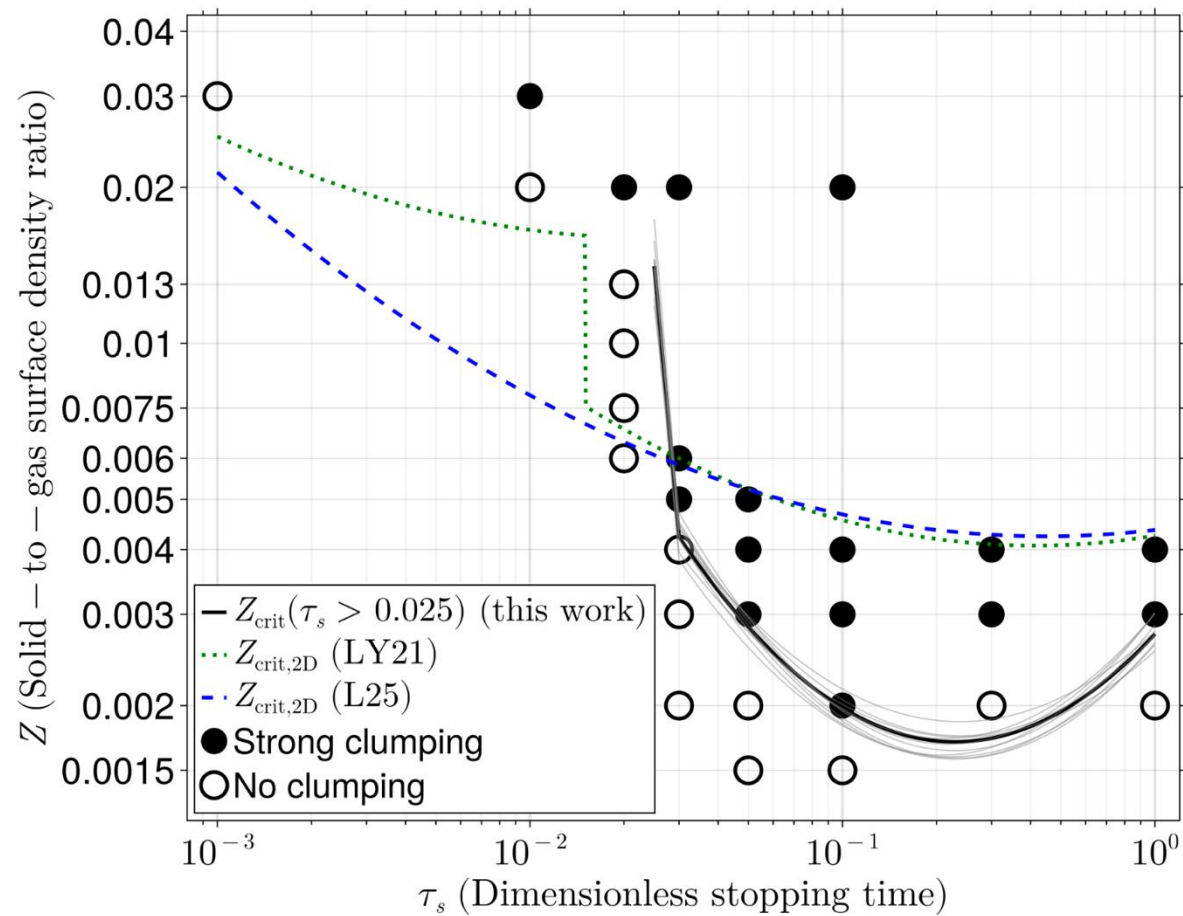
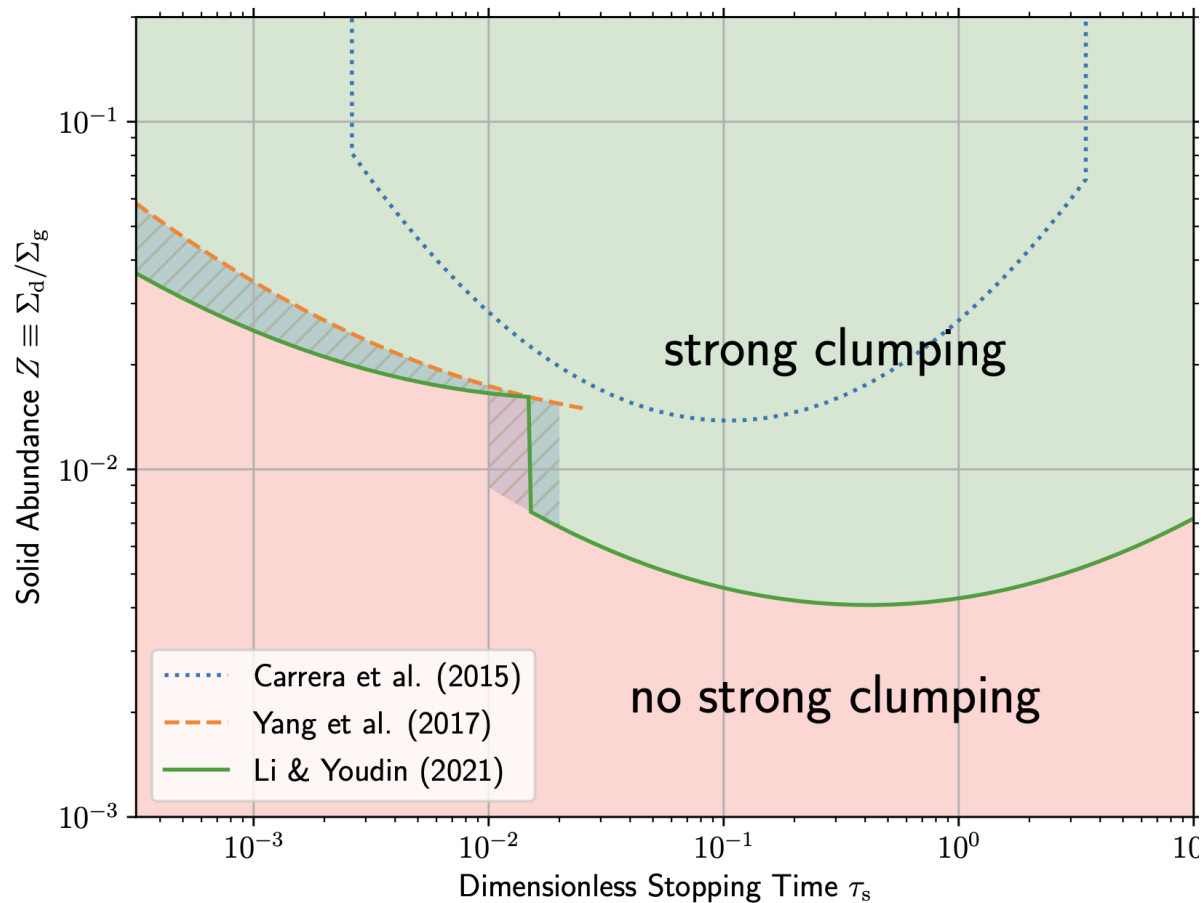
Stochasticity: Athena++ vs. PLUTO particles



Agreement must be inherently statistical

Code	Method	Dust	Flux Integration		Reconstruction		Time	
			Gas	Dust	Gas	Dust	Integrator	Order
Athena++	FV	Particles	HLLE ^f	...	PPM	...	VL2 ^q	2nd
PLUTO	FV	Particles	Roe	...	PPM	...	RK2	2nd

Follow-up: Clumping Boundary



Planetesimal Formation: Special locations vs continuous area

Special locations: **Snowline**, **viscosity transitions** (dead/active zone of any instability), **planetary gap edges**

A&A 487, L1–L4 (2008)
DOI: 10.1051/0004-6361:200809780
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&
Astrophysics**

LETTER TO THE EDITOR

Planetesimal formation near the snow line in MRI-driven turbulent protoplanetary disks

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Astrophysics**

Trapping solids at the inner edge of the dead zone: 3-D global MHD simulations

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ABSTRACT

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Astrophysics**

Planet formation bursts at the borders of the dead zone in 2D numerical simulations of circumstellar disks

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ABSTRACT

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GRAIN RETENTION AND FORMATION OF PLANETESIMALS NEAR THE SNOW LINE IN MRI-DRIVEN TURBULENT PROTOPLANETARY DISKS

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Astrophysics**

LETTER TO THE EDITOR

Embryos grown in the dead zone

Assembling the first protoplanetary cores in low mass self-gravitating circumstellar disks of gas and solids*

W. Lyra¹, A. Johansen², H. Klahr³, and N. Piskunov¹

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**Astronomy
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Astrophysics**

Standing on the shoulders of giants

Trojan Earths and vortex trapping in low mass self-gravitating protoplanetary disks of gas and solids

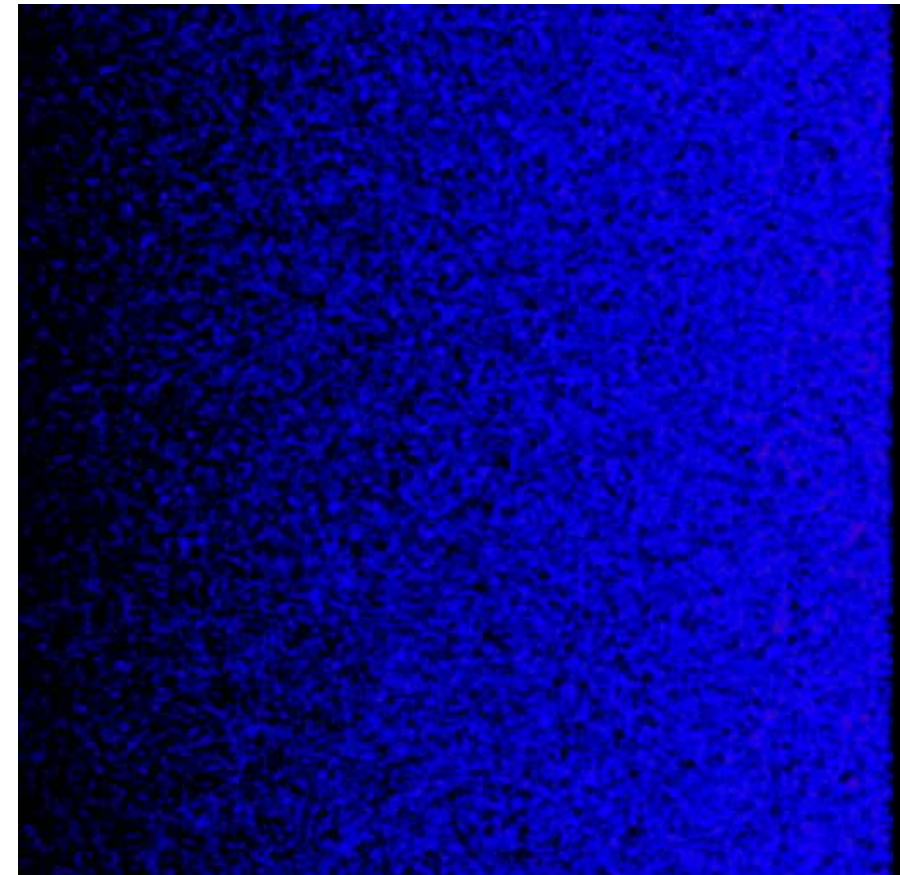
W. Lyra¹, A. Johansen², H. Klahr³, and N. Piskunov¹

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e-mail: wlyra@astro.uu.se

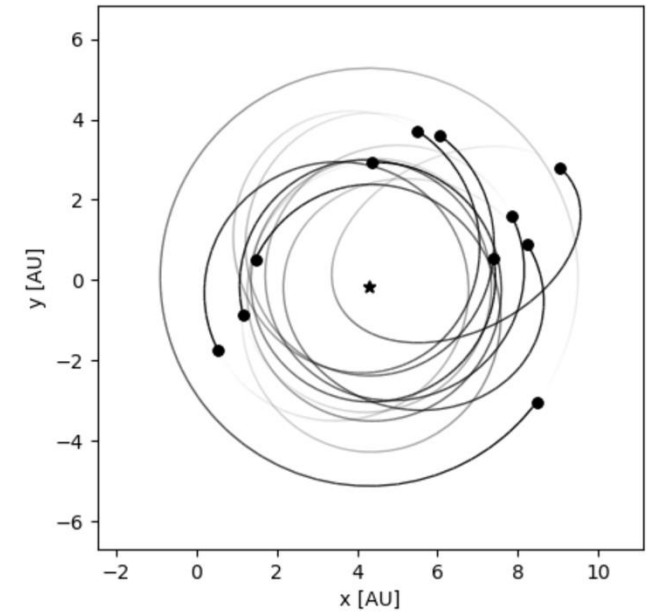
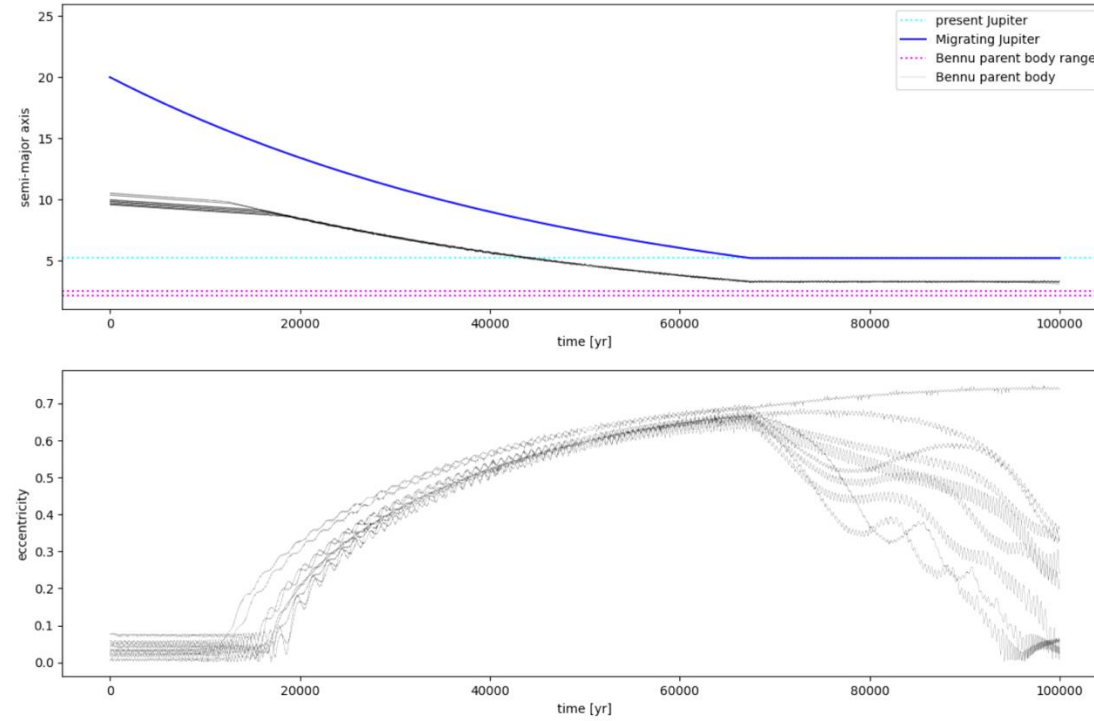
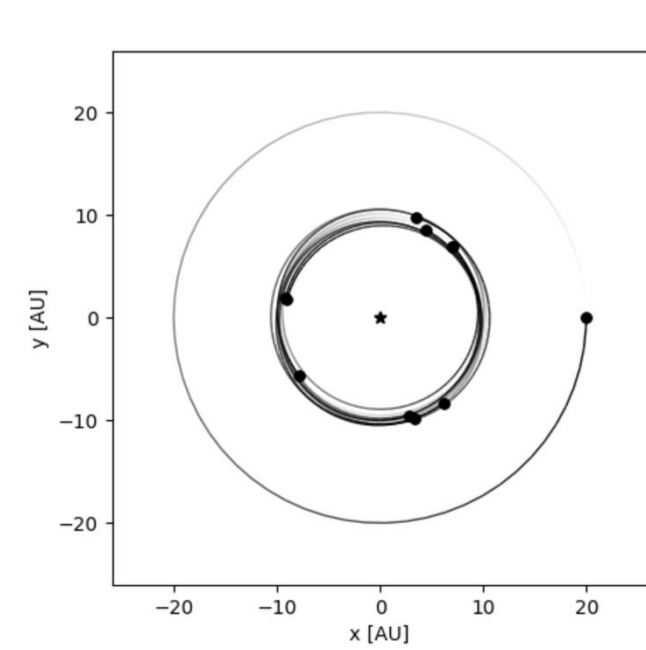
² Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands

³ Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

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Bennu parent body



Sub-gridscale collapse

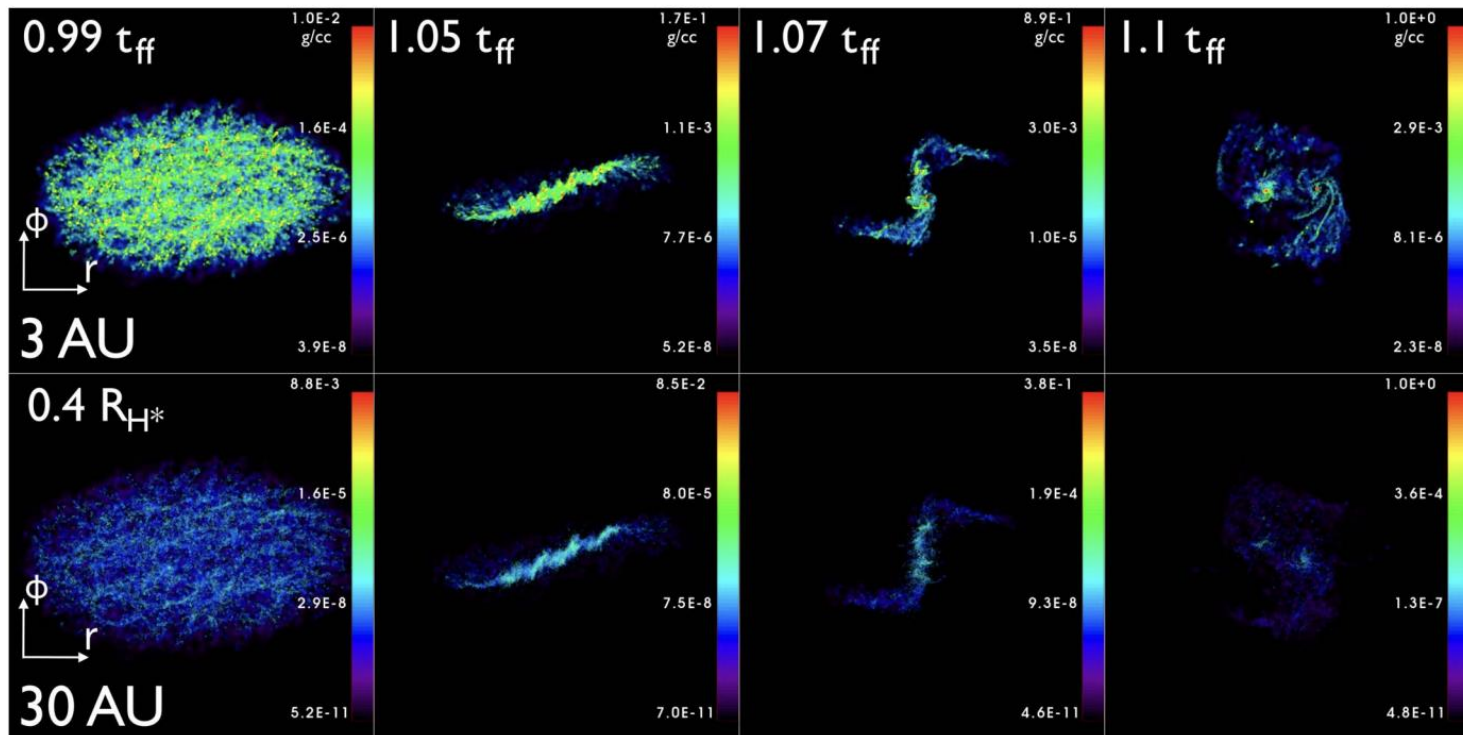
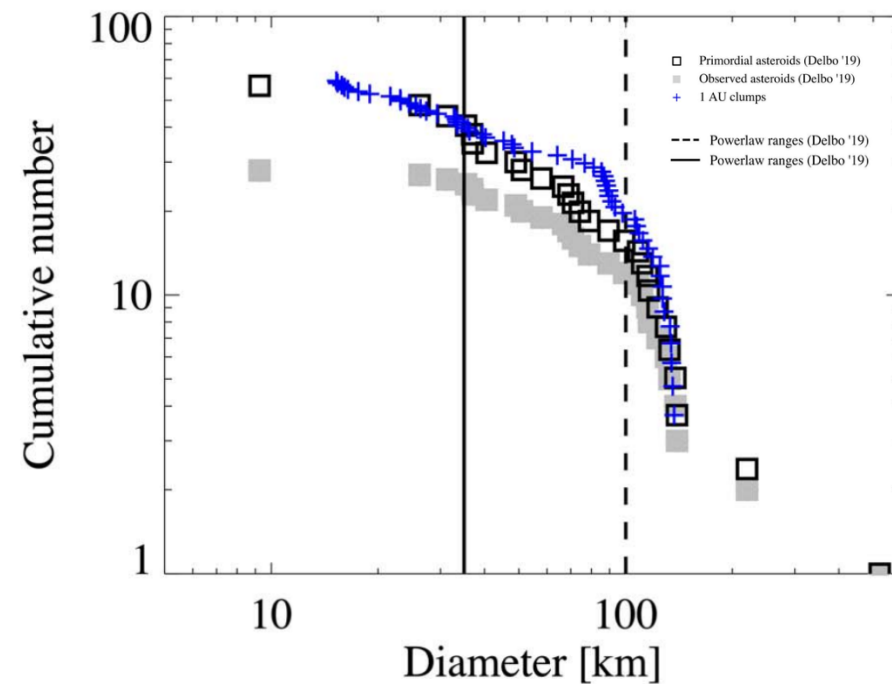


Figure 2. Density projection plots in the x - y plane of collapses at 3 and 30 au for a $1M_{\odot}$ star. For both the 3 and 30 au case, times are given in the upper panel in units of freefall time, and the scale of the horizontal radius is given in the bottom panel in units of the initial cloud radius.



Sub-gridscale collapse :Evidence for 1-10 km-sized “mounds”?

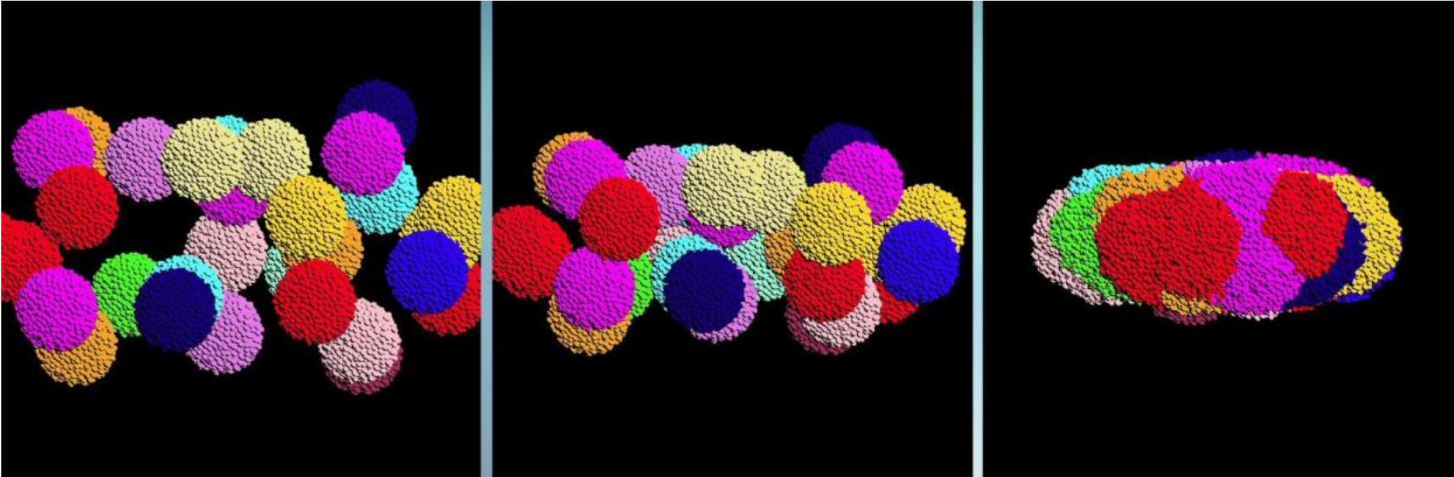
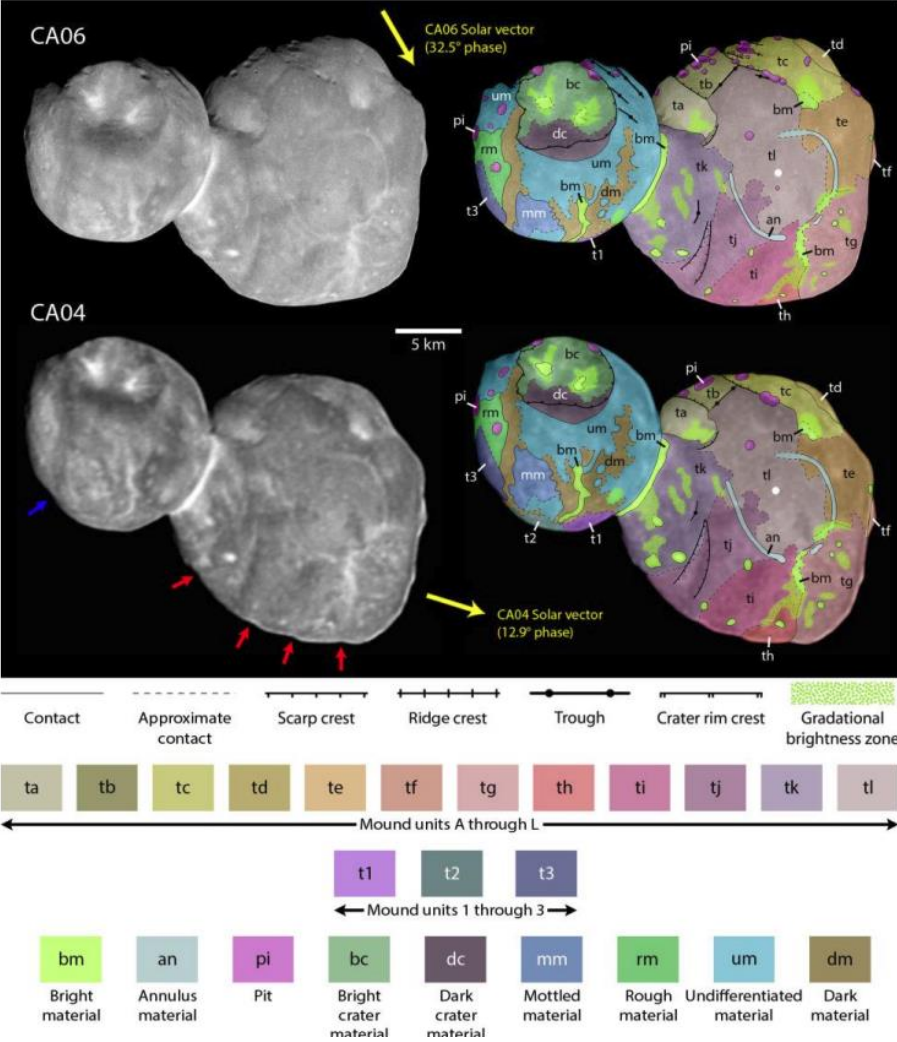
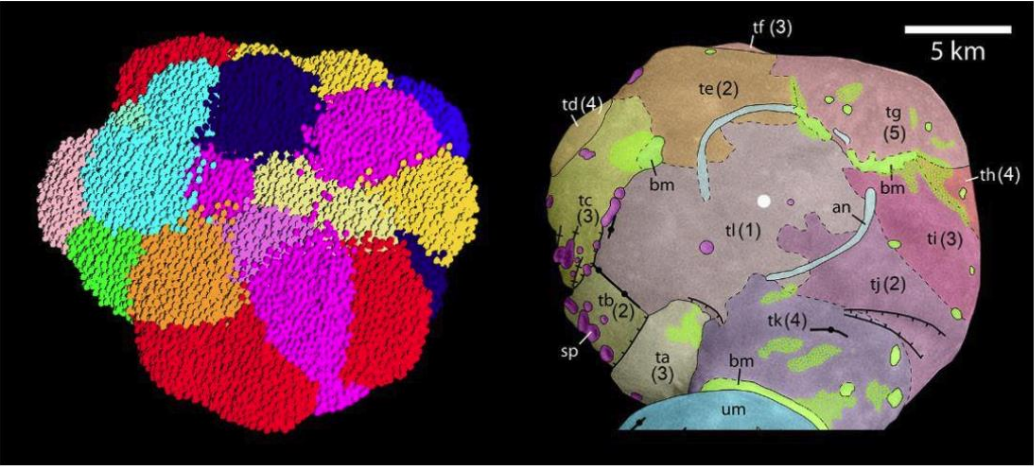


Figure 7. Three snapshots from the nominal PKDGRAV simulation of Wenu's accretion from 30 progenitors ~5 km in diameter.



Dust Models

- High densities matter for **planetesimal formation thresholds**
 - At 1024^2 , particle–fluid differences **shrink (~50% gap)**
 - Dust fluid sims should use a higher minimum grid resolution ($> 256^2/H^2$)
- Particle methods
 - Trades fluid grid errors for **interpolation errors, reduced with better kernels**
 - **Load-balancing** issues for performance
- Fluid methods
 - **No stream crossing** (cf. moment-method radiation transport)
 - May crash under steep gradients (finite-difference Pencil code)
- Neither model clearly superior among results
 - **Advanced fluid models** emerging (Binkert 2023; Lynch & Laibe 2024)

Conclusions

- All codes capture the same SI progression:
growth → **filaments** → **turbulence**
- **Dust model** is the main source of variation;
 - particles reach higher densities than fluids
 - (hint of convergence?)
- **Convergence** improves at higher resolution
 - **Fluids** need finer grids
 - **Particles** face higher cost from load-imbalance
- Agreement inherently **statistical**.